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## of the
# Optical Society of America

Devoted to All Branches of Optics

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## MARCH–MAY 1917

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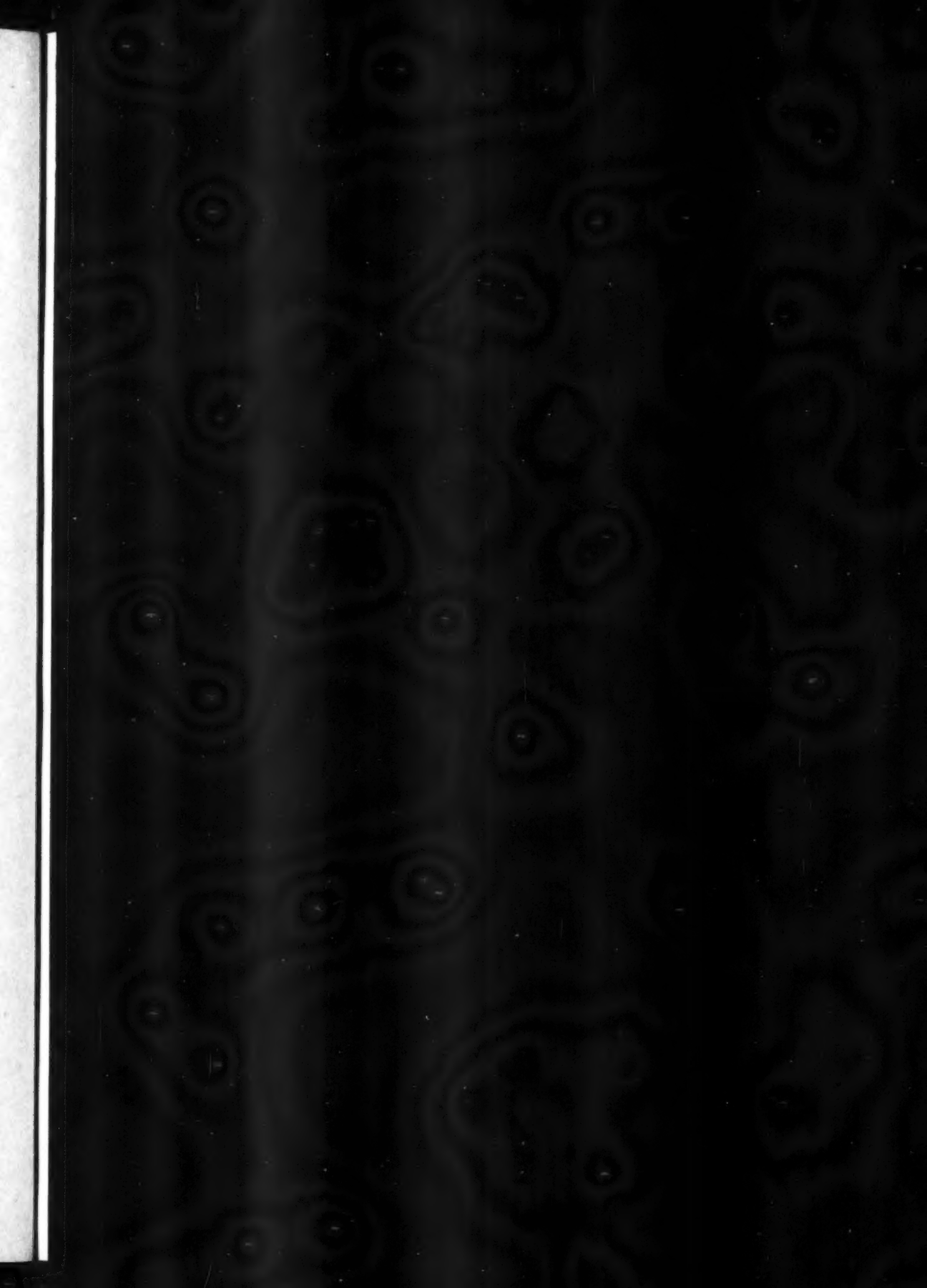

Journal

OF THE

Optical Society of America

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Volume 1 MARCH—MAY, 1917 Numbers 2 and 3

# LIPPMANN COLOR PHOTOGRAPHS AS SOURCES OF MONOCHROMATIC LIGHT IN PHOTOMETRY AND OPTICAL PYROMETRY

By HERBERT E. IVES

Synopsis

1.—Introduction.

2.—Preparation of monochromatic Lippmann films.

3.—Application to photometry.

(a) Theory of the Crova method of color difference photometry.

(b) Construction of a special eye-piece for the Lummer-Brodhun photometer head.

(c) Calibration and use of the special eye-piece.

4.—Application to optical pyrometry.

## 1.—INTRODUCTION

The Lippmann color photograph consists essentially of a fairly transparent film of gelatin in which lie thin layers or laminae of reflecting material. These laminae are produced by the action of standing waves of light on the originally photographically sensitive film, caused by reflection of the incident light back through the film from a reflecting surface in contact with it, the reflecting surface being usually of mercury. In the case of monochromatic light the loops of these standing waves, where the

photographic action takes place, are distant from each-other half the wave length of the light. Upon illuminating such a laminated film by white or continuous spectrum light, the reflected light is monochromatic, consisting of a series of pulses separated by twice the separation of the laminae, that is, by the wave-length of the originally active light. The film thus constitutes a *color photograph*.[1]

As such photographs are ordinarily developed, by the procedure best adapted for the rendering of mixed colors, monochromatic colors are rendered with great loss of purity. It was indeed thought for a long time that the number of laminae possible to be formed was necessarily few, owing to absorption and scattering of the incident light in the film. The present writer found, however, a number of years ago,[1] that the standing waves are actually formed with monochromatic light not only throughout the depth of the film but to a distance equivalent to many film thicknesses. It is only necessary to substitute for the usual pyrogallic acid developer, which acts on the surface of the gelatin, a developer like hydrokinone, which acts throughout the depth, to have the laminae developed from front to back of the film. Owing to the great absorption of these laminae the amount of light reflected is insufficient, but upon bleaching the film with mercuric chloride, a transparent opalescent deposit is left in which the laminae are layers of different refractive index from the unaffected gelatin. The final product is a multiple reflecting surface which returns light of a very high degree of spectral purity. In place of the broad diffuse band which the ordinary Lippmann photograph of monochromatic light shows in the spectroscope these specially prepared photographs show a narrow line of light, which is narrower the greater the depth of the film, as it should be according to the theory. On transmission they show a narrow black line in the spectrum similar in appearance to the Fraunhofer lines of the solar spectrum.[2]

In describing these films originally the writer suggested that they might find uses as simple sources of monochromatic light. The present paper describes two such uses. Doubtless there are many others, some of which will occur to readers upon seeing how the present applications have been made.

---

[1] For information on the Lippmann color photograph and the technique of its production, see "An Experimental Study of the Lippmann Color Photograph," Ives, Astrophysical Journal XXVII, 5, 1908, p. 325.

[2] Such a medium providing a single absorption line located where desired might have applications where a reference line is needed, as in objective prism stellar spectroscopy.

The first use to be described is in connection with color difference photometry. One of the well-known methods of eliminating color difference, applicable where the illuminants under comparison have continuous spectra, is the Crova method, which consists in carrying out the observations by monochromatic light of wave-length selected to give results equivalent to those given by the elaborate methods necessary for the direct measurement of illuminations different in color.[3] The means usually employed for securing the required monochromatic light have been either colored solutions, or spectroscopic devices. The former labor under the two disadvantages that they do not transmit light of great spectral purity, so that a difference of hue usually remains in the photometer field, and that the equivalent wave-length cannot be changed. This latter is a serious disadvantage, for while Crova's original idea was that one wave-length would do for all illuminants it actually proves that some variation is necessary. The spectroscopic devices can of course give any required degree of spectral purity and also permit this variation of wave-length, but are apt to be complicated and expensive, besides wasting a great deal of light over and above what is inevitable in any scheme for securing monochromatic light.

The Lippmann film as made by the procedure developed by the writer makes possible all the spectral purity that would ever be practical to utilize from a spectroscopic device. It possesses moreover a very interesting property which makes it peculiarly applicable to the Crova method. This property is that *the wave-length of the reflected light changes with the angle of observation*. The film therefore has all the desirable characteristics of the spectroscopic device, with the advantage, however, as will be seen, that it is far simpler to make and use.

The second use which is suggested is in optical pyrometry. Here the Lippmann film offers itself solely as a substitute for the spectroscope or colored glass by which observation is ordinarily made. It is simpler than the spectroscope, and renders more monochromatic light than a colored glass.

## 2.—PREPARATION OF MONOCHROMATIC LIPPMANN FILMS.

The Lippmann plates used in the present investigation were made up according to the writer's formula [1] by the Research Laboratory of the

[3] See "The Application of Crova's method of Colored Light Photometry to Modern Incandescent Illuminants," Ives & Kingsbury, Trans. Illum. Eng. Soc., X, 8, p. 716, 1915.

Eastman Kodak Company. They were flowed on an ordinary plate-making machine, which as it proved, was not entirely a satisfactory procedure, because the coating is not as uniform in thickness as can be obtained by hand flowing individually leveled plates. The resulting non-uniformity prevented the carrying through of a study of the best conditions and treatment for securing the maximum brilliancy of reflected light, which was planned, and should be carried through should the production of these films in any quantity be undertaken.

A mercury tank plate-holder, as described in the earlier account of the writer's original work, was used for making the films in the usual manner. As a source of monochromatic light when red and orange light were wanted a monochromatic illuminator was employed with a carbon arc lamp, the image of the crater being focused on the slit. For yellow and yellow-green light a bright sodium flame [4] was employed, which proved very satisfactory when placed about a foot from the plate, necessitating 15 to 30 minutes' exposure. The greater purity of the color rendering from films exposed to truly monochromatic light, as compared with the result which can be got with any practicable slit width in a spectroscopic device for giving monochromatic light, points to the desirability of making the red and orange films by light from a source giving a line spectrum, such as the cadmium arc. The wave-length rendered by the film, as viewed at nearly normal incidence, is very nearly that of the source. Some shrinkage of the film occurs in development, but this is compensated for by a swelling after the mercuric chloride treatment. It differs slightly also from film to film exposed to the same original wave-length, depending on the time of development, washing, etc.

After development and drying the films were put in shape for use by having mounted on them three degree prisms,[5] to throw to one side the first surface reflections, and the back of the glass plate was blackened. Both the prism surface in contact with the Canada balsam which was used for cementing, and the back of the glass were roughened with emery to dull such reflection as they would ordinarily give. Asphaltum varnish mixed with gutta percha dissolved in benzole was used as a black paint which would be unlikely to become brittle and chip off, as asphaltum alone will in time.

[4] "Note on the Production of a Very Intense Sodium Flame," Phil. Mag. XXVII, p. 530, 1914, R. W. Wood.

[5] Obtainable from any spectacle lens manufacturer.

### 3.—APPLICATION TO PHOTOMETRY

(a) Theory of the Crova method of color-difference photometry.

The photometry of lights of different color is a matter of some difficulty, partly owing to the difficulty of forming a judgment, and partly owing to the differences existing in the color vision of different observers. Methods have been worked out for making such comparisons satisfactorily, but they belong in the standardizing laboratory. Simple means for making this kind of measurement, with results agreeing with the standard method, are desirable for other laboratories, and are furnished by various devices to eliminate the color difference in the actual photometric observation, these devices being themselves the subject of calibration in the standardizing laboratory. Colored absorbing media, whose transmissions have been determined at the standardizing laboratory, and which reduce the light of a given illuminant to visual similarity with that of the standard, are an illustration in point.

Another means of eliminating color difference is the use of monochromatic light for observation, where by "monochromatic light" is meant light of sufficiently narrow spectral extent so that no difference in hue can be distinguished when the "monochromatic" bands as obtained from any two light sources to be measured are compared in the photometric field. Given sufficiently monochromatic light, the main problem in the use of this, the "Crova" method, is the selection of the proper wave-length to insure that the results of its use will agree with the renderings of the standard photometric method. Obviously the method is applicable only to light sources having continuous spectra, which however constitute the majority of the common illuminants.

Three methods may be employed to determine the correct Crova wave-length; the first, by the experimental procedure of trial and error; the second, by graphical calculation, using the known energy distribution of the light sources and the visibility curve of the spectrum; the third, applicable to sources whose energy distribution follows laws expressible in mathematical form, by numerical calculation. For the first method it is necessary to know from previous work the relative intensities of two light sources, which are of the kind with which it is expected to use the method in later practice. Then, with apparatus such as a spectroscopic eye-piece, by which the wave-length of observation may be varied, the wave-length may be picked by trial for which the intensities of illumination

from the two sources are the same as for the total light as previously established by the approved standard photometric method.

The second method is illustrated fully by the diagram, figure 1. a and b are respectively the energy distribution curves of the two illuminants

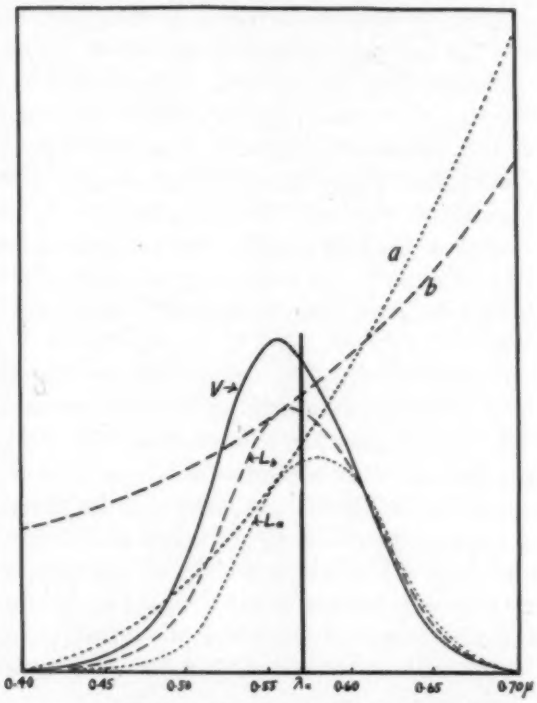



Fig. 1. Illustrating the theory of the Crova method.
a—energy distribution of light source A.
b—energy distribution of light source B.
V—visibility curve or luminosity curve of equal energy spectrum.
$L_a$ and $L_b$—luminosity curves of A and B.
$\lambda_c$—wave-length for which the values of a and b have the relative values of $L_a$ and $L_b$.

under comparison, as determined by a suitably sensitive radiometer, or by spectrophotometric comparison with some source of known energy distribution, such as the black body. V is the visibility curve, or luminosity curve of the equal energy spectrum for the normal eye, as established by the standard photometric procedure. $L_a$ is the luminosity curve of the source a, as obtained by forming the product, wave-length by wave-length,

of curves a and V. Similarly $L_b$ is the luminosity curve of source b. The *areas* of these luminosity curves are directly proportional to the luminous intensities of the sources. Upon measuring them, as with a planimeter, it is at once possible to pick that wave-length $\lambda_c$ for which curves a and b have the same relative values as these areas, and this wave-length is the Crova wave-length.

The third method is exemplified by the black body, using the Wien equation to represent its visible energy distribution, and a suitable equation to represent the visibility curve. Thus if we wish to find the Crova wave-length for use in comparing black bodies at temperatures $T_1$ and $T_2$, we first perform the integration for each temperature of the expression

$$L = \int_0^\infty c_1 L_\lambda \lambda^{-5} e^{-\frac{c_2}{\lambda T}} d\lambda \tag{1}$$

Where L is the area of the luminosity curve, $c_1$ and $c_2$ are black body constants, $L_\lambda$ is the visibility at wave-length $\lambda$. From these integrations we obtain the ratio of $L_{T_1}$, to $L_{T_2}$. We now seek the wave-length for which the intensities of emission of the two black bodies are in the ratio $\frac{L_{T_1}}{L_{T_2}}$. This is given by solution of the equation

$$\frac{L_{T_1}}{L_{T_2}} = e^{-\frac{c_2}{\lambda}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)} \tag{2}$$

An expression for $L_\lambda$ and values of L for the black body have been calculated by Kingsbury,[6, 7] so that the left-hand side of equation (2) may be written from mere inspection of tables.

By the use of these methods it is readily seen that data could be obtained for the construction of a table from which the wave-length to be used in the comparison of any one illuminant with any other could be constructed. A still simpler table can however be constructed by making use of the idea of *equivalent wave-lengths*, the meaning of which may be best grasped by consideration of the equivalent wave-lengths in the case of the black body.

If in equation (2) the temperature interval is made infinitesimal the Crova wave-length becomes that wave-length at which the intensity is changing for any small temperature change in either direction from T at the same rate as the luminosity. This wave-length is then the *equivalent wave-length* for the temperature T. Values for this equivalent wave-length

[6] "A Spectral Luminosity Curve Equation and its Use," Kingsbury, Physical Review, VII, 2, Feb. 1916, p. 161.

[7] "Note on Black Body Brightness Equations Based on Equivalent Wave-Lengths," Ives & Kingsbury, Physical Review VIII, 3, Sept. 1916, p. 323.

have been calculated and tabulated[6]. Now it is easily found by test that the Crova wave-length for comparing black bodies at two temperatures is equal, for all practical purposes, to the *mean of the equivalent wave-lengths*. The practical value of this is that the equivalent wave-length is obtainable from a very simple formula whereby the necessary calculations are greatly reduced. This formula is as follows:

$$\lambda_c = 0.545 + \frac{77}{T} - \frac{6000}{T^2} \tag{3}$$

The use of these equivalent wave-lengths is, strictly speaking, confined to illuminants whose visible energy distribution is that of a black body at some temperature. It is however permissible to extend the idea to other light sources. For, suppose it has been found by experiment that the Crova wave-length for comparing a certain light source with a black body whose equivalent wave-length is $\lambda_1$, is $\lambda_2$, then we can say that as far as that particular comparison is concerned we can assign to the light source an equivalent wave-length $\lambda_3$ such that the mean of $\lambda_3$ and $\lambda_1$ shall be $\lambda_2$ or

$$\lambda_3 = 2\lambda_2 - \lambda_1 \tag{4}$$

Now, although this equivalent wave-length in general holds only for the particular comparison made, we find that, owing to the narrowness of the visibility curve, which restricts all Crova wave-lengths for artificial illuminants to a small spectral region near 0.58$\mu$, no serious error is likely if this same equivalent wave-length is used in all comparisons. In other words, if the equivalent wave-length is determined in the manner described, using black bodies at several temperatures for the comparison light, the same value will be found to within the limits of accuracy of the measurement, provided of course that the illuminant has a continuous spectrum of no markedly selective character.

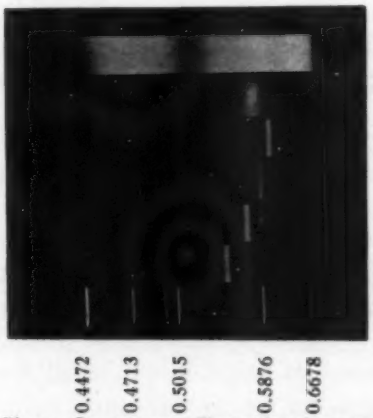



Fig. 2. Spectrograms illustrating characteristics of Lippmann films of use in photometry.
a—continuous spectrum of tungsten lamp.
b—transmission of "Crova" solution, consisting of a mixture of potassium dichromate and cupric chloride.
c, d, e and f—light reflected by Lippmann film at $x°$, $(x + 5)°$, $(x + 10)°$, $(x + 20)°$.
g—spectrum of helium gas.

The result of the utilization of this conception of equivalent wave-lengths is that, instead of the Crova wave-length table being one of as many rows

as columns, it is only necessary to have a single column containing equivalent wave-lengths, with the understanding that the Crova wave-length to be used is the mean of the equivalent wave-lengths of the compared illuminants.

(b) Construction of a special eye-piece for the Lummer-Brodhun photometer head.

The peculiar applicability of the Lippmann film to the Crova method is illustrated by the spectrograms of Fig. 2. Here the upper spectrum is that of a tungsten lamp; next is the transmission spectrum of a very monochromatic cupric chloride + potassium dichromate solution, which has been used for the Crova method[3]; below it in order are the reflection spectra from a typical film (exposed to sodium light), when turned through a series of angles differing by steps of five degrees. Both the excellent monochromatic character of the reflected light, and the control of its wave-length are exhibited.

The incorporation of one of these films in a photometer head is a problem which could be solved in a variety of ways. The greatest difficulty is offered by the fact that the film must be observed by reflected light, which means that the line of sight of the observer must be very differently directed than is usual, unless an additional reflection is resorted to. The design actually adopted is shown diagramatically in Fig. 3, and in the photograph, Fig. 4. The device for utilizing the films consists of an attachment to the Lummer-Brodhun photometer head, screwing on in place of the regular eye-piece. It consists essentially of a revolving table, carrying the film, and an eye-piece, mounted to rotate about the same axis as the film. The direction of the line of sight varies with the angle of the film, from parallel to the photometer track, around toward a right angle to it. The minimum angle corresponds, because of the characteristic 45° position of the Lummer-Brodhun eye-piece, to a deviation of the reflected from the incident rays of this same angle. The immediate consequence of this is that the greatest wave-length available is considerably shorter than the wave-length used in making the film. In the case of the wave-lengths utilized in the Crova method (near 0.58$\mu$) this means that the taking wave-lengths must be in the red or orange-red. This, the price to be paid in order to avoid a second reflecting surface, is no disadvantage at all for this particular use, although it might be if a greater range of the spectrum were called for, because of the limitation of sensitiveness of the Lippmann plates (sensitized with pinacyanol and erythrosin) in the deep or infra-red.

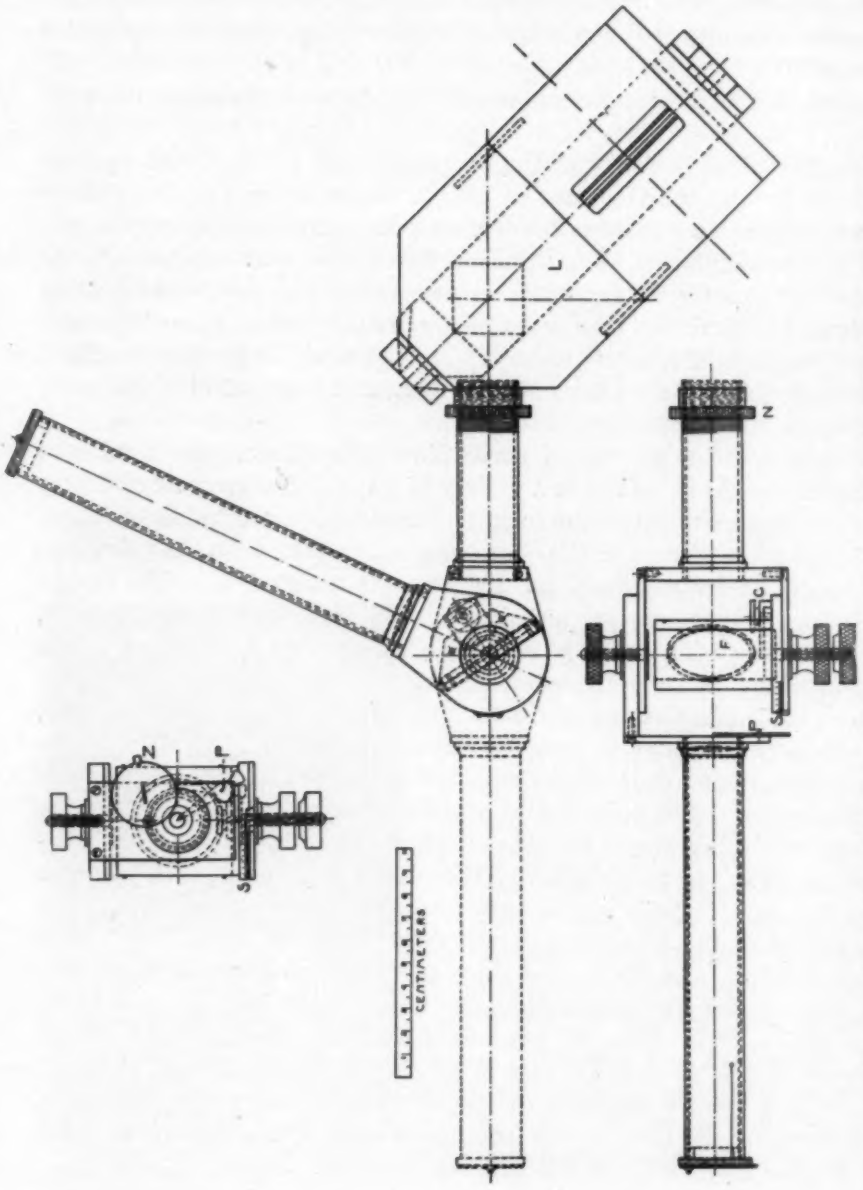



Fig. 3. Diagram of special Lippmann film eye-piece attachment for Lummer-Brodhun Photometer Head.

L—Lummer-Brodhun head.
N—Lock-nut for holding eye-piece to photometer head.
F—Frame holding Lippmann film.
C—Clamp for holding film frames in place on dowel pins.
S—Scale for reading position of film frame.
Z—Eye-slit for aid in alignment.
P—Pointer for aid in alignment.

Details of construction are given in the figure. Several films being available they were mounted on similar frames, provided with dowel pins so that they could be interchanged if desired. The operation of putting a film in place to use is quite simple. After being clamped to the revolving

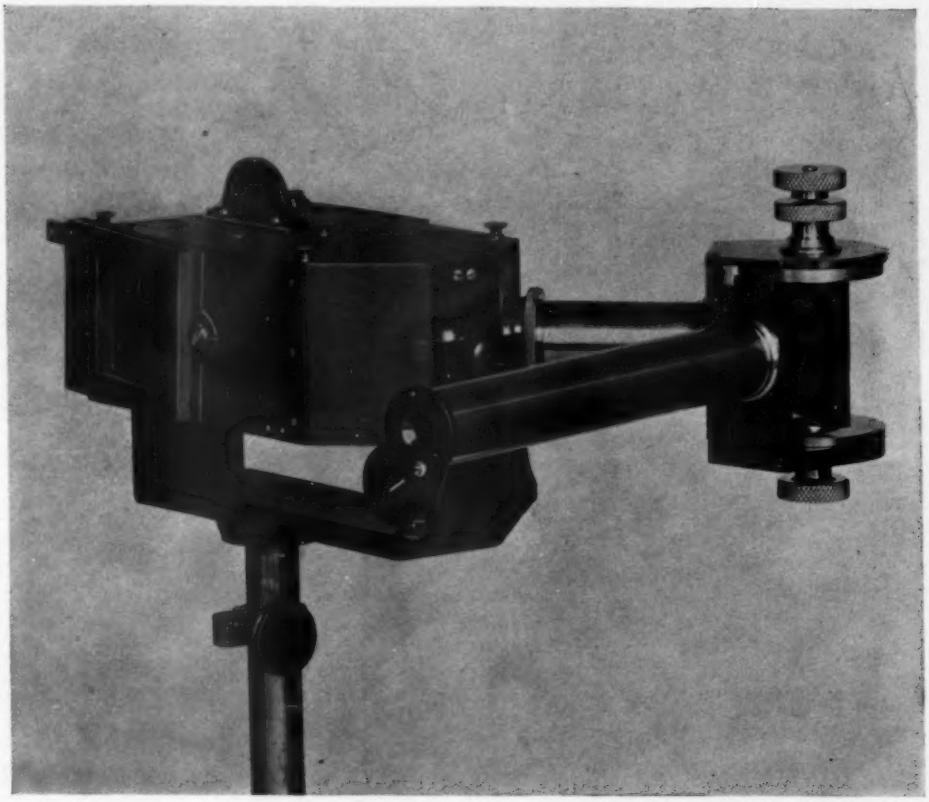


Fig. 4

table it is turned to the proper angle on the scale S to give the required wave-length (as read from the calibration sheet), and clamped. The eye-piece tube is then turned until the pattern of the photometric field is central. This latter setting is made accurate by means of the pointer P, and the narrow eye-slit Z, which are thrown into position temporarily, and which with the center line of the photometer cube pattern form three points on a straight line when the adjustment is correct.

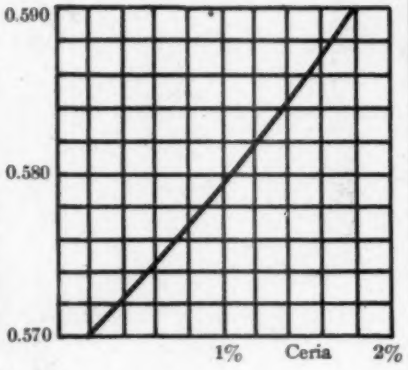
## DATA ON LIPPMANN-CROVA EYEPIECE

*To use.*—Set film to mean of *equivalent wave-lengths* of illuminants to be compared, as given by table below, and proceed as in ordinary photometry.

*Instructions for setting film to any wave-length.*—Read corresponding angle from wave-length-angle-calibration of film to be used (number of the film in the upper left-hand corner of the mount). Set film mount in position by dowel-pin and clamp, turn until scale reads correct angle: Turn slit over eye end of eye-tube and throw pointer at film end to its extreme position. Turn eye-tube until tip of pointer appears on center-line of photometer field. Throw slit and pointer out of way and proceed.

| TABLE OF EQUIVALENT WAVE-LENGTHS | |
|---|---|
| Illuminant | λe |
| Hefner — — — — — — — | 0.586μ |
| Pentane— — — — — — — | 0.584 |
| Standard(4w.p.c.)carbon. Open flame gas | 0.581 |
| 3.1 w.p.c. carbon — — — — | 0.580 |
| 2.5 w.p.c. G.E.M. — — — — | 0.579 |
| 1.25 w.p.c. tungsten — — — — | 0.577 |
| 1.0 w.p.c. tungsten — — — — | 0.576 |
| 0.65 w.p.c. gas filled tungsten — — | 0.574 |

MANTLES




WAVE-LENGTH-ANGLE CALIBRATION

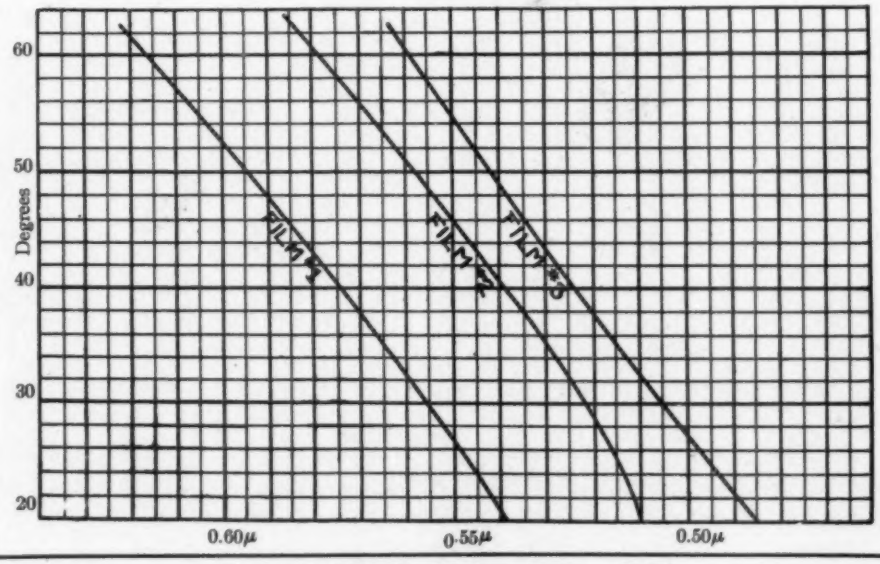



Fig. 5. Data sheet for Lippmann-Crova eyepiece.

(c) Calibration and use of the special eye-piece.

The first process of calibration necessary with this apparatus is to obtain the wave-length-angle relation for the films in their mounts. This was done by the aid of a simple grating spectrometer, consisting of the eye-piece slit already mentioned, a grating replica through which this was observed, and a photographic scale placed at the position in space where the spectrum is seen. The whole spectrometer turned with the eye-tube to which it was attached, and the calibration process consisted in reading off the position of the center of the observed band in the spectrum, on the scale which had been previously evaluated against a bright line source. The result of this calibration process for three of the films is plotted in the data sheet reproduced in Fig. 5.

The second part of the calibration consists in the determination of the equivalent wave-lengths of those illuminants with which the apparatus was expected to be used. For the flames and incandescent electric illuminants which accurately match the black body at some temperature it was only necessary to know the "color temperature" and then calculate the equivalent wave-lengths by formula 3. These "color temperatures" were taken from recent work by Hyde, Patterson and others, the values used being:

| | *Color Temperature.* | |
|---|---|---|
| Hefner | 1830°K | |
| Pentane | 1882°K | |
| "4-watt" carbon | 2080°K | —(Color of open gas flame) |
| "1.25 w. p. c." tungsten | 2330°K | |
| "1 w. p. c." tungsten | 2425°K | |
| ".65 w. p. c." gas-filled tungsten | 2600°K | |

The corresponding equivalent wave-lengths are shown in the data sheet. The accuracy of these was tested by comparison of the results obtained by their use with the results from using the "electric Crova"[3] solution worked out some time ago to give values in agreement with the photometric scale maintained in our laboratory. The agreement was found to be satisfactory.

The equivalent wave-lengths for the Welsbach mantles of different ceria content were obtained by the empirical method described as the first method above. Mantles of 0.25, 0.75 and 2% ceria were measured

against a standard carbon lamp, first, with the "gas Crova solution" previously developed, and then by the use of a series of wave-lengths obtained from the films. The correct wave-length for making the observation was then read off from the plotted results. Equivalent wave-lengths calculated on the assumption discussed earlier are plotted in the small chart on the data sheet.

With the aid of this eye-piece and its accompanying data sheet the photometrist is equipped to measure all of the ordinary illuminants, without ever actually seeing a color difference. It is probably the most convenient means as yet developed for the elimination of color difference. It suffers of course from the inherent defect of all monochromatic light devices of being deficient in light. This necessitates rather careful shielding of the eye, and working with as short distances between photometer head and light source as possible. The low brightness of the photometer field as observed by monochromatic light results in some loss of precision with a small number of settings, easily overcome by making enough settings to offset scattering, but not, as would be the case if color differences were being observed, in loss of accuracy.

The actual amount of light available with the most brilliant films is at least as much as could be obtained by a spectroscopic eye-piece.

## 4.—APPLICATION TO OPTICAL PYROMETRY

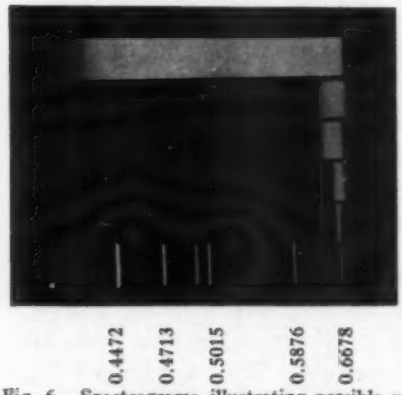



Fig. 6. Spectrograms illustrating possible use of monochromatic Lippmann film in optical pyrometry.
a—continuous spectrum of tungsten lamp.
b—red glass used in commercial optical pyrometer.
c and d—good quality monochromatic red glasses.
e—Lippmann film.
f—helium vacuum tube spectrum.

The spectrograms in Fig. 6 show the purity of the red light transmitted by a red glass in a commercial optical pyrometer, and by two red glasses manufactured by one of the prominent makers of colored glass in this country, probably as monochromatic as any made. The fifth spectrum (e) is the light reflected from a red Lippmann film. The greater purity of this light suggests the possibility of using such films in optical pyrometers as a substitute for glasses. They should give practically as pure light as can be utilized by a spectroscopic device, certainly pure enough to obviate

corrections for shift of the equivalent wave-length with change in the temperature of the source.

The actual preparation of an optical pyrometer incorporating one of these films has not yet been undertaken, but experimental trials with the essential optical parts of the Holborn-Kurlbaum type of instrument show that this could be easily done. The problem not being complicated by the necessity for varying the wave-length is simply one of substituting the reflecting Lippmann film for the transmitting glass, using mirrors or reflecting prisms to bring the line of sight in a convenient direction.

THE UNITED GAS IMPROVEMENT CO.
Physical Laboratory
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# THE FUNDAMENTAL SCALE OF PURE HUE AND RETINAL SENSIBILITY TO HUE DIFFERENCES[1]

By L. A. JONES

When radiant energy is incident upon the retina of a normal eye the sensation of light is produced. This sensation may be said to consist of two factors, brightness and color, the former being dependent upon the intensity and the latter upon the quality of the incident radiation. The quality of the radiation may be specified by stating its wavelength, in case radiation of but one frequency is present; or in case it is composed of a mixture of many frequencies, by stating the wavelength and intensity of each of the component elements. The curve representing the relations existing between the intensity and wavelength of such mixed radiation, commonly called a spectrophotometric curve, is usually plotted with intensity factors as ordinate and wavelengths as abscissa values.

Such a curve constitutes a complete physical specification of the quality of the radiation and hence of color. The retina, however, being a synthetic rather than an analytic receiving organ does not recognize the individual component parts of the radiation as such, but receives the mixed radiation as a single stimulus producing a single color sensation. Hence, a spectrophotometric curve, while entirely satisfactory from a physical or objective standpoint, does not constitute a physiological specification of the color of

[1] Communication No. 44 from the Research Laboratory of the Eastman Kodak Company. Presented before the Optical Society of America at the New York meeting held December 28, 1916.

the visible radiation, and it is necessary to provide other means for the satisfactory specification of color as such.

Subjectively, that is, from the standpoint of the subjective sensation, color may be said to consist of two factors, hue and purity or saturation. Hue refers to the position in the spectrum of the dominant quality, while purity expresses the proximity of the color to the condition of monochromatism.

It has been demonstrated experimentally that any color can be matched by the mixture, in the proper proportions, of white light with monochromatic light of the proper wavelength. In this way a direct measurement of the fundamental properties of a color may be made; the hue being specified by the wavelength of the monochromatic light used (wavelength of the dominant hue) and the purity or saturation by the ratio of the intensity of the white light to that of the monochromatic light (per cent. white).

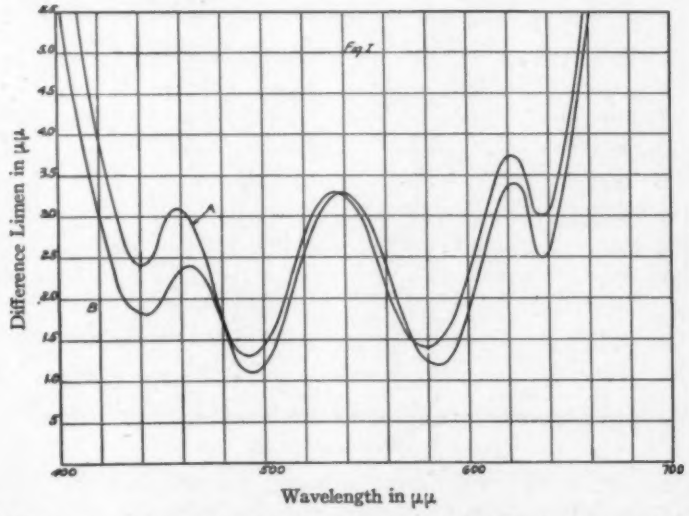
An exception to this general rule is encountered in case the color to be matched is a purple or magenta. In such cases some mixture of the color with monochromatic light can be made by which sensation white will be produced, the terms of the color specification then being the wavelength of the complementary dominant hue and the per cent. of monochromatic light in the mixture (per cent. hue).

It is evident then, since hue must be expressed in terms of the wavelength of the radiation, that if a hue scale is to be established the points on that scale must be designated in wavelength units. The first requirement of a scale for the measurement of any quantity is that the unit used shall be of a fixed magnitude and of the same value throughout the scale. It has been found, however, that equal wavelength differences do not produce equal color sensation differences throughout the sensation scale being considered. Hence, the wavelength unit is not suitable for use as a unit in the establishment of a scale of subjective color sensation.

It seems to be most logical, therefore, and in fact the only alternative, to adopt as the unit for such a scale the least perceptible color sensation difference and to assume that this sensation unit (difference limen) is equal at all points in the sensation scale. The question as to whether or not the difference limen is equal at all points on any sensation scale has been discussed at great length by philosophers and psychologists, and seems to be capable of settlement in either direction by the proper course of metaphysical reasoning. However, from the standpoint of a physicist it seems

entirely reasonable to make the difference limen at all points on a sensation scale equal by definition and to adopt this least perceptible difference as a sensation unit and to use it for the establishment of sensation scales.

The problem, then, in the establishment of the fundamental hue scale is to determine for the entire range of visible radiation the relation existing between the wavelength unit and the sensation unit (the least perceptible color sensation difference). Such a relation having been determined, the difference limen—wavelength curve can be plotted. Since the greater the difference limen the less the sensibility, the sensibility can be taken as proportional to the reciprocal of the difference limen; and the sensibility curve of the retina to hue difference may be plotted from the data on difference limen. By integrating this sensibility curve, since a scale-reading curve can be obtained by the integration of the sensibility curve,[2] the scale-reading curve necessary for the establishment of the fundamental hue scale can be obtained. Or by adopting the difference limen as a unit, the hue scale may be determined by direct experimental measurement and, if desired, the sensibility curve can be obtained by differentiation of this scale-reading curve.



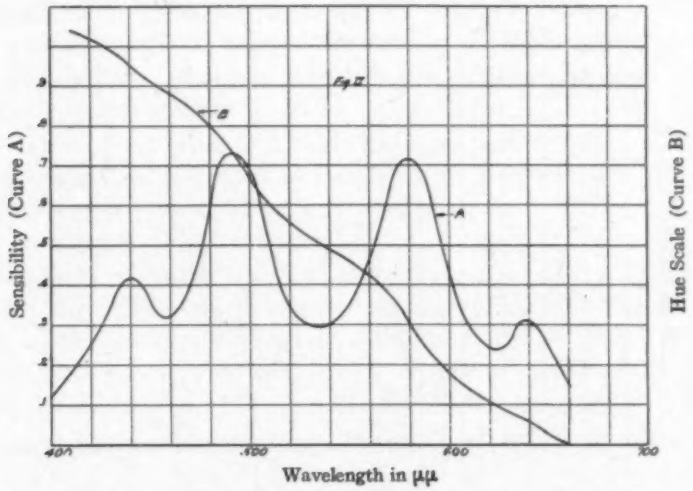

The first step, then, in the establishment of the fundamental hue scale is the determination of precise values (in terms of wavelight units) for the average normal human eye of the least perceptible hue differences (the

[2] Nutting, P. G., Bulletin of Bureau of Standards, Vol. 5, p. 266, 1908.

sensation unit) throughout the visible spectrum. The final values, then, must be the result of the proper summarization of a large amount of data obtained from the study of a large number of different individuals having normal vision.

Steindler [3] has made measurements on the hue sensibility of twelve subjects, all having normal color vision. The average curve (difference limen—wavelength) for these twelve individuals is shown in Fig. I, curve A.

This curve was obtained by treating the original data as suggested by Nutting,[4] that is by averaging the values of wavelength and limen for each maximum and minimum. The values obtained and given in column F of Table I are slightly different from those obtained by Nutting, the differences representing the variations due to personal judgment in drawing curves through a series of plotted readings. In Fig. II, curve A is the hue sensibility curve obtained by computing the reciprocal values from the limen curve, and curve B is the scale-reading curve obtained by the integration of the sensibility curve.

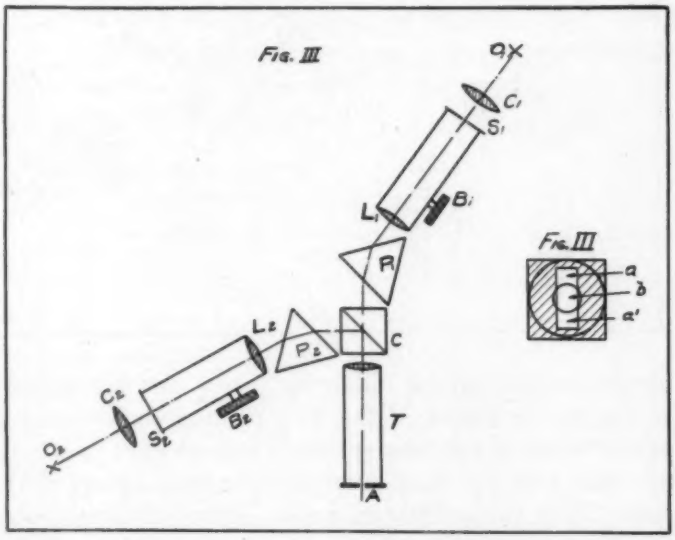



In view of the fact that Steindler's data are the average for only twelve subjects, it seemed desirable to obtain further data on difference limen of other individuals, and for this purpose the following work was carried out. The measurement of the required difference limen involves the measurement

[3] Steindler, O., Ak. Wiss., Wien, 115, 2a., Jan. 1906.

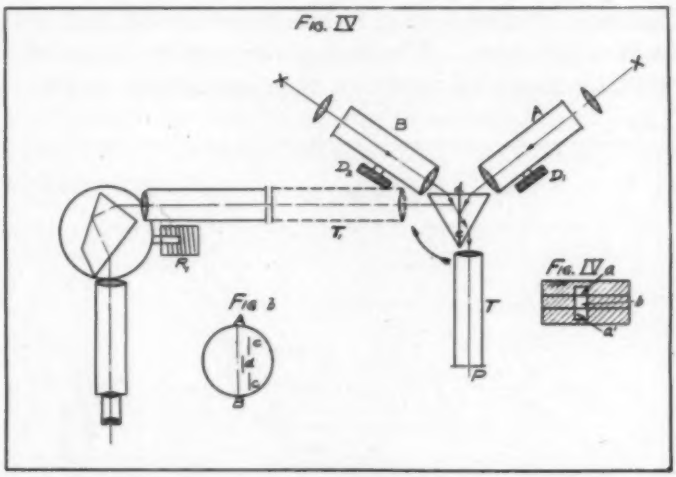
[4] Nutting, P. G., Bulletin of Bureau of Standards, Vol. 6, p. 89, 1909-1910.

of the difference in the wavelength of the light illuminating two fields which appear just perceptibly different in hue; since the desired scale is that of pure hue, fields illuminated by light as nearly monochromatic as possible must be used. Hence, apparatus giving very pure monochromatic light of easily measurable and variable wavelength in connection with some type of two part photometer field, each part of which may be illuminated independently by monochromatic light of variable quality and intensity, must be employed. It is very important that the intensity be easily controllable, for in making a judgment of equality or difference of hue it is necessary to maintain an intensity balance between the two fields in order that the judgment of hue may not be influenced or confused by the existence of an intensity difference. The first instrument constructed for the fulfillment of these conditions is shown diagrammatically in Fig. III. It con-




sisted essentially of two 60° prisms, $P_1$ $P_2$, used in connection with a photometer cube C, two collomating systems, $O_1$, $C_1$, $L_1$, and $O_2$, $C_2$, $L_2$ and an observing telescope T equipped with a pinhole ocular A. The dispersed light from one system, $O_1$, $P_1$, illuminated one field of the photometer cube, and that from the other system, $O_2$, $P_2$, illuminated the other portion of the photometric field. The photometer cube used was of the Lummer-Brodhum

type having concentric circular fields, and by placing a rectangular diaphragm on the surface of the cube facing the telescope, T, a field of the type shown in Fig. IIIa was obtained. When viewed through the pinhole ocular, A, of the telescope, T, the fields a, a′, appeared to be illuminated by approximately monochromatic light from the $S_1$, $P_1$, system, and the field, b, by similar light from the $S_2$ $P_2$ system. The angular positions of the collomating systems were controlled by the micrometer screws $B_1$, $B_2$, calibrated to read the wavelength of the light illuminating the respective fields of the cube. The intensity of the light was controlled by the adjustable slits, $S_1$, $S_2$.

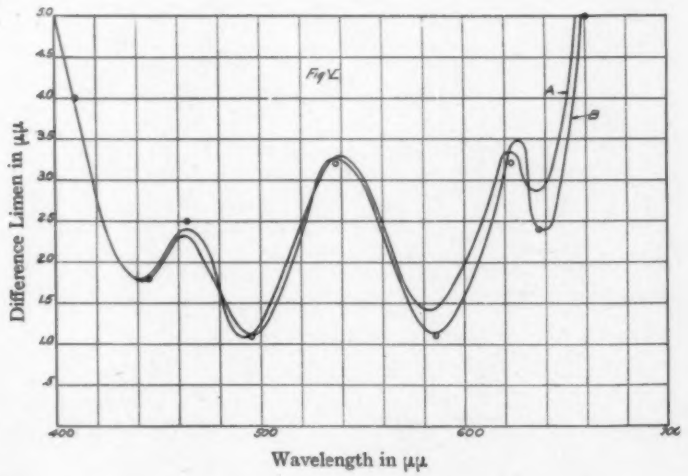



The determination of the difference limen was accomplished by adjusting the angular positions of the two collimating systems until a just perceptible difference in hue was apparent between the two portions of the photometric field, and by then obtaining the wavelength difference from readings taken from the calibrated scales. The value thus obtained gave the difference limen for a point in the spectrum midway between the two wavelength values read from the calibrated scales. Several readings were made at each point and at many different points throughout the visible spectrum, a difference limen— wavelength curve being plotted from the values thus obtained.

Considerable data were obtained with this instrument which in many ways were found to be very satisfactory, but due to certain mechanical

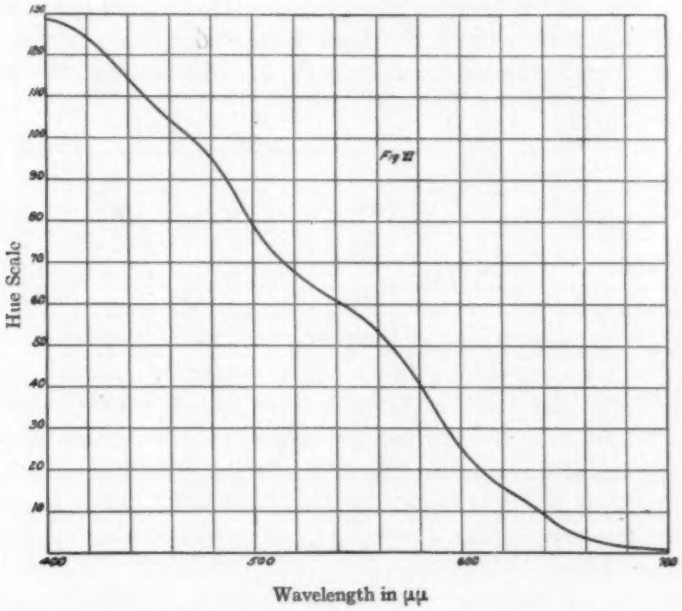
defects this was discarded and the work continued with improved apparatus. This consisted of a Brace spectrophotometer used in connection with a Hilger spectroscope of the constant deviation type.

The arrangement of parts is shown in Fig. IV. It is unnecessary to describe this apparatus in detail, both instruments being well known. Here again were two collomating systems A and B, their angular position being adjustable by means of the micrometer screws, $D_1$, $D_2$. The prism consisted of two 30° elements cemented together along the line cd, thus forming a compound 60° prism. On one of the cemented faces was a narrow silvered strip (about 8 mm wide), parallel to the base of the prism, and centrally placed in the vertical direction. By observing through the pin-hole ocular, P, of the telescope, T, over the object glass of which was placed a diaphragm with a rectangular opening, a field of the type shown in Fig. IVa was seen. The portions of the field, a, a′, appeared to be illuminated by monochromatic light from the system B, and the area b by light from system A. How this is accomplished may be seen by an inspection of the diagram. The wavelength of the light in the two parts of the field was controlled independently by the screws $P_1$, $P_2$, the intensity by adjustable slits $S_1$, $S_2$.




The entire system just described, including light sources, condensers, etc., was mounted on a table which could be rotated about a point in such a manner as to bring the telescope, T, into alignment with the collimating

system of the Hilger spectroscope. By looking through the eyepiece of the Hilger instrument and by bringing the lines in the field onto the cross line of the eyepiece, the wavelength of the light entering the slit, from the fields a, a′ and b of the spectrophotometer, could be accurately measured. The field appeared as is shown in Fig. V. AB is the reference line of the eyepiece, c, c′, are the lines due to the light coming from the portions a, a′, (Fig. IVa) of the spectrophotometric field, and d is the line due to that from the portion b (Fig. IVa). The wavelength of each could be precisely measured by bringing them one after the other into coincidence with the reference line, AB, reading the values directly from the calibrated wavelength drum R, Fig. IV. Or the wavelength of the light from the two fields could be made equal by rotating either $D_1$ or $D_2$ (Fig. IV) until the three segments c, d, c′, formed a continuous straight line. The difference limen was measured in the usual way and the sensibility and scale-reading curves computed.




In Fig. VI are shown two complete limen curves, curve A being plotted from data obtained with the first instrument, and curve B from limen data taken with the Brace-Hilger apparatus. These curves agree very well in

shape and in magnitude of the limen values. They also agree quite well with Steindler's mean curve (Fig. I), showing the same typical maxima and minima. The limen values agree fairly well with those of Steindler except in the blue end between 400 $\mu\mu$ and 470 $\mu\mu$. This lack of agreement will be mentioned again later in the discussion. The values of the wavelength and limen for the maxima and minima of curves A and B (Fig. VI) are given in columns A and B of Table I.

Another method was also used in taking data with the second arrangement of apparatus. This gave a direct determination of the scale-reading curve and involved the use of the least perceptible hue difference as the actual unit of measurement. Starting at a given point the entire spectrum was measured off step by step with the difference limen as the unit of length. This method gives the total number of just perceptibly different hues present in the spectrum and the distance apart of these equal sensation steps in terms of the wavelength unit. The number of distinct hues found by the author in a very careful set of reading was 128 between 400 $\mu\mu$ and 700 $\mu\mu$. By plotting the consecutive wavelength readings as abscissae against equal ordinate increments (since these readings correspond to equal sensation steps) the scale-reading curve was obtained directly. The curve thus obtained is shown in Fig. VI. This curve may be differentiated and the sensibility curve obtained and from that the limen-wavelength curve by taking reciprocal values, or the wavelength value of each step may be plotted directly against the mean wavelength of each interval and the limen curve obtained in that way. The small circles in Fig. VI show the positions of the maxima and minima (values tabulated in columns C, Table I) of the curve thus obtained and again show good agreement with previous values.

In Table I are given the values of the wavelength and limen for the maxima and minima of four separate determinations made by the author.

The method involving the measurement of the limen values at certain points in the spectrum (every 5 $\mu\mu$ or every 10 $\mu\mu$) is called, for sake of convenience, the *discontinuous* method, and that involving progression through the entire spectrum step by step, thus measuring each just perceptibly different hue, is termed the *continuous* method.

In Table I the data in column D were obtained with the left eye and are not so reliable as those obtained with the right, the variations in the values being quite large. Column E contains the averages of the values tabulated under A, B, and C (data on left eye are not included) and may be

TABLE I

| | A | | B | | C | | D | | E | | F | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | λ | dλ | λ | dλ | λ | dλ | λ | dλ | λ | dλ | λ | dλ |
| At λ = 660..... | 660 | 6.0 | 660 | 5.2 | 660 | 5.0 | 660 | | 660 | 5.4 | 660 | 6.0 |
| First Minimum .. | 635 | 2.8 | 638 | 2.4 | 637 | 2.4 | 635 | 3.1 | 637 | 2.5 | 637 | 3.0 |
| First Maximum.. | 622 | 3.4 | 628 | 3.5 | 623 | 3.2 | 620 | 3.7 | 624 | 3.4 | 621 | 3.7 |
| Second Minimum. | 584 | 1.4 | 585 | 1.2 | 586 | 1.1 | 584 | 1.4 | 585 | 1.2 | 580 | 1.4 |
| Second Maximum | 538 | 3.5 | 540 | 3.3 | 537 | 3.2 | 538 | 3.0 | 538 | 3.3 | 535 | 3.3 |
| Third Minimum.. | 596 | 1.2 | 490 | 1.1 | 595 | 1.1 | 486 | 1.0 | 594 | 1.1 | 592 | 1.3 |
| Third Maximum. | 462 | 2.3 | 465 | 2.4 | 564 | 2.5 | 465 | 1.9 | 464 | 2.4 | 458 | 3.1 |
| Fourth Minimum. | 442 | 1.8 | 443 | 1.8 | 445 | 1.8 | 454 | 1.5 | 443 | 1.8 | 440 | 2.4 |
| At λ = 410..... | 410 | 4.0 | 410 | 4.6 | 410 | 4.0 | 410 | 5.0 | 410 | 4.2 | 410 | 5.5 |

Column A..... 1st determination with right eye (discontinuous)
" B..... 2nd " " " " "
" C.....3rd " " 1 " " (continuous)
" D..... 1st " " left " (discontinuous)
" E..... Mean values of A, B and C.
" F..... " " from Steindler data (12 subjects)

compared with column F, the values from Steindler's data. The mean curve obtained by averaging the three sets of data obtained with the right eye is shown as curve B, Fig. I, in order that its shape and the magnitude of the limen values may be easily compared with the mean of Steindler's data. It will be noted that the values of curve B agree very well with those of A from about 470 to 580 $\mu\mu$, and that in the red and yellow from 580 to 660 the curve B shows limen values only slightly less than those of A. In the blue and, however, from 410 to 470 the limen values of B are considerably less than those of A. The position in the spectrum of the various maxima and minima are nearly the same in the two curves.

The excess sensibility to hue differences in the blue end of the spectrum, in the case of the curve B, may be in some way related to the slightly excessive brightness sensibility of the author's right eye for that region of the spectrum. Some years ago the author was one of a group of several (about 10) observers making a photometric comparison of carbon and tungsten candle power standards. In reading the tungsten against a carbon standard the author consistently obtained values about 3% higher than the average of the whole group of observers, thus showing a slightly excessive sensibility to the brightness of the tungsten lamp (blue in color as compared to the

carbon); this excess being, of course, only relative to that particular group of observers. It seems entirely possible, therefore, that the hue sensibility curve of any individual may also indicate something concerning his brightness sensibility.

The results so far indicate that an observer can repeat results on hue limen fairly well and that the limen—wavelength curve for an individual has a very definite shape. The data in Table I (A, B and C) indicate a slight increase in sensibility (decrease in limen values) with the experience of the observer in taking the readings. This increase, however, is quite small, in fact scarcely large enough to be taken as conclusive evidence of the increase of sensibility due to practice in observing. A comparison of the data in columns D and E indicates that no marked differences are to be expected between the hue sensibility characteristics of the right and left eye of an individual having normal color vision.

In Table II are given the values obtained by the continuous method starting at 700 $\mu\mu$ and going through the spectrum step by step to 400 $\mu\mu$. The Hue Number is merely the number of the hue in the series starting with 700 $\mu\mu$ as No. 1. The wavelength column gives the wavelength (in $\mu\mu$) of each consecutive hue, and the "$d\lambda$" column the wavelength interval between that particular hue and the preceding one. It is desired to emphasize again the point that the interval between any two consecutive hue numbers is the fundamental sensation unit (the least perceptible difference) and hence the series of hues given by the wavelength values in column 2 forms a series on the sensation scale separated by equal sensation steps.

Now referring to the scale reading curve, plotted from these same values, in Fig. VI; suppose that a series of points separated by equal intervals be laid off on the hue scale (y axis) and a series of horizontal lines be drawn through these points cutting the scale-reading curve. Now the wavelength values obtained by projecting these points of intersection on the wavelength axis (x axis) will represent a series of spectral hues separated by equal sensation steps. Or by the inverse process, starting with the wavelength values, it is easy to determine whether any series of hues are separated by equal or unequal sensation steps.

It is proposed now to apply this method of analysis to one of the best systems of color standards. This system was devised and worked out by Robert Ridgway, Curator of the Division of Birds, U. S. National Museum, and is described in detail and illustrated with eleven hundred and fifteen

TABLE II

| No. | λ(μμ) | dλ(μμ) | No. | λ | dλ | No. | λ | dλ |
|---|---|---|---|---|---|---|---|---|
| 1 | 700.0 | —— | 44 | 576.5 | 1.4 | 87 | 490.4 | 1.1 |
| 2 | 678.0 | 22.0 | 45 | 75.2 | 1.3 | 88 | 89.4 | 1.0 |
| 3 | 665.0 | 13.0 | 46 | 73.7 | 1.5 | 89 | 88.2 | 1.2 |
| 4 | 659.0 | 6.0 | 47 | 71.7 | 2.0 | 90 | 87.0 | 1.2 |
| 5 | 654.0 | 5.0 | 48 | 70.1 | 1.8 | 91 | 85.8 | 1.2 |
| 6 | 49.5 | 4.5 | 49 | 68.4 | 1.7 | 92 | 84.5 | 1.3 |
| 7 | 46.0 | 3.5 | 50 | 66.6 | 1.8 | 93 | 83.2 | 1.3 |
| 8 | 42.8 | 3.2 | 51 | 64.8 | 1.8 | 94 | 81.7 | 1.5 |
| 9 | 40.2 | 2.6 | 52 | 63.0 | 1.8 | 95 | 80.0 | 1.7 |
| 10 | 37.8 | 2.4 | 53 | 61.1 | 1.9 | 96 | 78.2 | 1.8 |
| 11 | 35.5 | 2.3 | 54 | 58.6 | 2.5 | 97 | 76.5 | 1.7 |
| 12 | 33.1 | 2.4 | 55 | 57.0 | 2.6 | 98 | 75.0 | 1.5 |
| 13 | 30.0 | 3.1 | 56 | 54.4 | 2.6 | 99 | 72.9 | 2.1 |
| 14 | 26.5 | 3.5 | 57 | 51.8 | 1.6 | 100 | 70.5 | 2.4 |
| 15 | 23.0 | 3.5 | 58 | 49.1 | 2.7 | 101 | 68.2 | 2.3 |
| 16 | 20.0 | 3.0 | 59 | 46.1 | 3.0 | 102 | 65.8 | 2.4 |
| 17 | 17.3 | 2.7 | 60 | 43.0 | 3.1 | 103 | 63.6 | 2.2 |
| 18 | 14.9 | 2.4 | 61 | 39.8 | 3.2 | 104 | 61.2 | 2.4 |
| 19 | 12.5 | 2.4 | 62 | 36.5 | 3.4 | 105 | 58.7 | 2.5 |
| 20 | 10.2 | 2.3 | 63 | 33.2 | 3.3 | 106 | 56.5 | 2.2 |
| 21 | 08.0 | 2.2 | 64 | 30.1 | 3.1 | 107 | 54.4 | 2.3 |
| 22 | 06.0 | 2.0 | 65 | 27.1 | 3.0 | 108 | 52.1 | 2.3 |
| 23 | 04.1 | 1.9 | 66 | 24.2 | 2.9 | 109 | 50.0 | 2.1 |
| 24 | 02.3 | 1.8 | 67 | 21.4 | 2.8 | 110 | 48.0 | 2.0 |
| 25 | 600.6 | 1.6 | 68 | 19.1 | 2.3 | 111 | 46.0 | 2.0 |
| 26 | 599.0 | 1.6 | 69 | 16.8 | 2.3 | 112 | 44.2 | 1.8 |
| 27 | 97.4 | 1.6 | 70 | 14.6 | 2.2 | 113 | 42.5 | 1.7 |
| 28 | 95.9 | 1.5 | 71 | 12.6 | 2.0 | 114 | 40.8 | 1.7 |
| 29 | 94.5 | 1.4 | 72 | 10.6 | 2.0 | 115 | 39.0 | 1.8 |
| 30 | 93.1 | 1.4 | 73 | 08.0 | 1.6 | 116 | 37.2 | 1.8 |
| 31 | 91.8 | 1.3 | 74 | 07.0 | 1.0 | 217 | 35.3 | 1.9 |
| 32 | 90.5 | 1.3 | 75 | 05.4 | 1.6 | 118 | 33.3 | 2.0 |
| 33 | 89.5 | 1.0 | 76 | 04.0 | 1.4 | 119 | 31.3 | 2.0 |
| 34 | 88.5 | 1.0 | 77 | 02.6 | 1.4 | 120 | 29.3 | 2.1 |
| 35 | 87.5 | 1.0 | 78 | 01.3 | 1.3 | 121 | 27.0 | 2.2 |
| 36 | 86.4 | 1.1 | 79 | 500.0 | 1.3 | 122 | 24.8 | 3.2 |
| 37 | 85.3 | 1.1 | 80 | 498.7 | 1.3 | 123 | 22.3 | 2.3 |
| 38 | 84.0 | 1.3 | 81 | 97.4 | 1.3 | 124 | 19.7 | 2.8 |
| 39 | 82.7 | 1.3 | 82 | 96.1 | 1.3 | 125 | 16.7 | 3.0 |
| 40 | 81.5 | 1.2 | 83 | 94.8 | 1.3 | 126 | 13.8 | 2.9 |
| 41 | 80.3 | 1.2 | 84 | 93.7 | 1.1 | 127 | 10.4 | 3.4 |
| 42 | 79.1 | 1.2 | 85 | 92.6 | 1.1 | 128 | 405.8 | 4.6 |
| 43 | 77.9 | 1.2 | 86 | 91.5 | 1.1 | | | |

TABLE III

| 1 No. | 2 Name | 3 Hue | 4 Purity | 5 dλ | 6 ds | 7 ds |
|---|---|---|---|---|---|---|
| *1 | Spectrum Red | 633 | 55 | — | — | — |
| 2 | | 616 | 31 | 17 | 5.0 | 5.0 |
| 3 | | 610 | 34 | 6 | 2.0 | 3.0 |
| 4 | | 605 | 34 | 5 | 1.5 | 2.0 |
| 5 | | — | — | — | 2.0 | 2.5 |
| *6 | Orange Chrome | 597 | 40 | 8 | 2.5 | 2.5 |
| 7 | | 595 | 34 | 2 | 1.5 | 1.5 |
| 8 | | 593 | 26 | 2 | 1.0 | 1.5 |
| 9 | | 589 | 23 | 4 | 2.0 | 3.0 |
| 10 | | 586 | 31 | 3 | 2.0 | 3.0 |
| 11 | | 582 | 34 | 4 | 2.5 | 3.0 |
| *12 | Lemon Yellow | 579 | 29 | 3 | 3.0 | 3.0 |
| 13 | | 577 | 34 | 2 | 2.0 | 2.0 |
| 14 | | 574 | 39 | 3 | 2.0 | 2.0 |
| 15 | | 569 | 42 | 5 | 3.0 | 3.0 |
| 16 | | 566 | 42 | 3 | 2.0 | 2.0 |
| 17 | | 548 | 47 | 18 | 6.0 | 8.0 |
| *18 | Emerald Green | 521 | 63 | 17 | 9.0 | 9.0 |
| 19 | | 518 | 66 | 3 | 2.0 | 2.0 |
| 20 | | 510 | 63 | 8 | 3.0 | 3.5 |
| 21 | | 495 | 55 | 15 | 10.0 | 10.0 |
| 22 | | 490 | 54 | 5 | 4.0 | 5.5 |
| 23 | | 486 | 51 | 4 | 3.0 | 3.0 |
| 24 | | 484 | 73 | 2 | 1.0 | 1.5 |
| *25 | Spectrum Blue | 479 | 70 | 5 | 2.0 | 2.5 |
| 26 | | 476 | 57 | 3 | 2.0 | 2.0 |
| 27 | | 470 | 62 | 6 | 3.0 | 3.0 |
| 28 | | 460 | 62 | 10 | 3.0 | 4.0 |
| 29 | | 445 | 58 | 15 | 5.0 | 8.0 |
| *30 | Spectrum Violet | 425 | 60 | 20 | 7.0 | 10.0 |
| | Mean | — | — | — | 3.2 | 3.8 |
| 31 | | 570 | 22 | — | — | — |
| 32 | | 559 | 15 | 11 | 5 | 6 |
| 33 | Purples | 555 | 13 | 4 | 2 | 2 |
| 34 | | 538 | 16 | 17 | 4 | 5 |
| 35 | | 534 | 11 | 6 | 3 | 2 |
| 36 | | 512 | 9.4 | 22 | 7 | 8 |
| | Mean | — | — | — | 4.2 | 4.6 |

named color standards in his book, "Color Standards and Nomenclature." The system is based on the correct principle of adopting both hue and purity scales based on equal sensation intervals. The scale of pure (spectral) hue consists of 30 units in the visible spectrum, separated by equal sensation intervals, and 6 units spaced through the purples (not present in the spectrum).

The difficulty of preparing color cards to represent these conditions lies in obtaining the proper pigments, it being impossible to find pigments which are monochromatic in their reflecting properties. However, it should be possible to prepare such color cards having the correct dominant hue and hence fulfilling the requirements of the hue scale although they must depart widely from the purity of the spectral colors.

In order to determine the spacing on the sensation scale of these thirty-six hue scale units, it was necessary to measure the dominant hue of each. This was done with a Nutting colorimeter, readings of both hue and purity being taken. The standard white used was midday sunlight, and all photometric readings of intensity being made by the flicker method. The actual samples used were cut from sheets obtained from the publisher, and it is entirely possible that some of these may differ slightly from those issued in Mr. Ridgway's book.

The colorimetric analyses of the thirty-six color standards of the hue scale are given in Table III. They are numbered (column 1) consecutively starting with the reddest red and ending with the reddest purple. The names (column 2) are those proposed by Ridgway. The dominant hue values (column 3) are in milli-microns ($\mu\mu$) and the purity values (column 4) are in per cent. white or per cent. hue. In column 5 are given the wave length intervals, $d\lambda$ (in $\mu\mu$), between the successive samples. In column 6 are given the values, in sensation units, of the corresponding intervals on the sensation scale, determined by use of the scale-reading curve of Fig. II (the curve obtained from Steindler's data). The values in column 7 are the similar values of sensation intervals obtained from the curve obtained by the author (Fig. VI).

The values in column 6 should be equal if the theoretical requirements of a uniformly grade sensation scale are fulfilled by the samples used. This, of course, also applies to the values in column 7. The amount of departure from uniformity in these values indicates the extent of failure in the fulfillment of the ideal conditions. The uniformity is quite good con-

sidering the practical difficulties encountered in the preparation of color standards. The mean value of the twenty-nine intervals included between the thirty spectral standards is in case of the Steindler curve 3.2, and for the author's curve 3.8. Taking the average of the two cases, this indicates that the sensation unit of the Ridgway hue scale is 3.5 least perceptible differences, the fundamental sensation unit.

It should be noted here that the samples used in this work have been recently compared with those issued in Mr. Ridgway's book, and several marked discrepancies found. Whether this is due to a fading of some of the samples or an error in their perforation is not known. It is proposed now to obtain, if possible, a new set of samples, one matching closely those issued with the complete set of color cards, and to redetermine the hue values. These will be published as soon as possible to replace the data presented at this time.

The present data, however, serve to illustrate the method for the establishment of hue scales having any desired sensation interval between the elements of the series, or for the determination of the sensation interval of any series of hue standards.

Much more data are needed for the establishment of the hue sensibility curve of the average normal eye, observations on a large number of different individuals being required. Work of this nature is being continued in this laboratory, and we hope in the near future to publish data on a considerable number of subjects.

The author wishes to acknowledge his indebtedness to Dr. P. G. Nutting for his many suggestions and aid in the design of apparatus used in carrying out the work of which this paper is a report. Also thanks are due Mr. Wagner, of Purdue University, for a large part of the work involved in making the colormetric analyses of the Ridgway color standards.

Research Laboratory
EASTMAN KODAK COMPANY
Rochester, N. Y.
*December 19, 1916*

# THE PREPARATION OF METALLIC MIRRORS, SEMI-TRANSPARENT AND TRANSPARENT METALLIC FILMS AND PRISMS BY DISTILLATION[1]

By Otto Stuhlmann, Jr.

The necessity for a quick, reliable and practicable method for making gas-free and pure transparent metallic films, which were to be used for some photo-electric and optical research, lead to the development of the following simple device for making transparent, half silvered and opaque silver reflectors. Those who have gone thru the tedious process of making and polishing silvered and half silvered surfaces, especially such as are used in interferometers, will appreciate a method which allows one to arrest and observe the development at all times in the process of deposition.

The essential part of the apparatus consists of a wire, heated to incandescence by means of an electric current, while the object to be covered with the metallic surface is placed below it. If the whole is now placed in vacuo, the metal will vaporize and condense upon the object. If the incandescent wire is now moved with uniform speed across the object, a uniform coat of the metal will be deposited. The thickness of this condensed metallic film depends on the time of deposit, the temperature of the wire, the molecular weight of the vapor and its vapor pressure.[2]

The accompanying figure shows an apparatus in use for the deposition of silver on concave, convex, plane and irregular surfaces. The material to be silvered can consist of anything not having a pronounced vapor pressure at room temperature and 0.002 mm. of mercury pressure.

The working parts were mounted on a thick plate of rolled brass, grooved to retain a circular bell jar BJ. Mercury or hard sealing wax floated into this groove, formed the seal for the vacuum. This was never less than 0.002 mm. of mercury pressure. The vacuum was obtained by means of a Gaede rotary mercury pump. The bell jar had an internal diameter of eight inches and was five inches high.

The carriage HE, supports the metal to be evaporated in the form of a wire, about 0.017 inches in diameter. The wire is fastened between the

[1] Abstract presented before Am. Phys. Soc., Dec. 26, 1916.

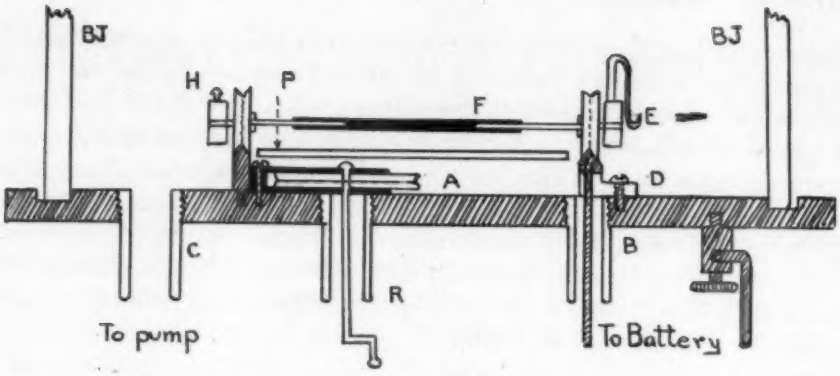
[2] Langmuir (Phys. Rev.V.2, p. 340, 1913) has shown that $m = \sqrt{\frac{M}{2\pi R T}}\, p$ where m is the rate of evaporation in vacuo, M the molecular weight of the vapor and p its vapor pressure.

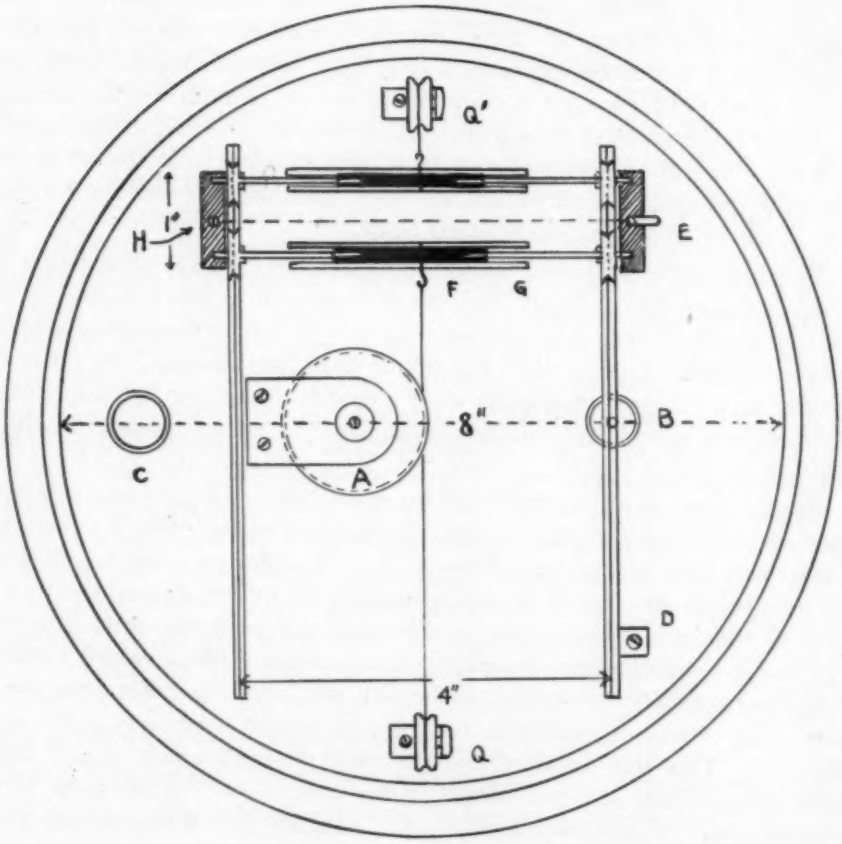
two points H and E as shown by the dotted line in the diagram. At H it is attached to a screw at the top of the rod connecting the two wheels, from where it passes down and then thru a large hole in the rod between the wheels, then across and thru a similar hole in the rod at E, thence to the spring brass hook. This springy hook supplies the necessary tension to the wire to keep it taut. Upon heating the wire, it expands and the slack is further taken up by the spring in the hook. A 110 volt alternating or direct source can be used for the heating current. Under these conditions a 0.017 inch silver wire needs about eight amperes to heat it enough to produce the desired vaporization.

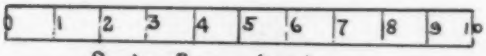
The heating current enters the inclosure thru the baseplate at the binding post to the right. It then passes into the metallic track at H which is screwed to the baseplate. From here it passes thru the left side of the carriage, thence thru the wire across to E into the right hand track. This track is insulated from the base by means of two fibre L-shaped supports. The current passes from this insulated track thru the rod B back to the battery. The rod B passes thru a hole in the base and is sealed in place with hard red sealing wax, which serves to insulate it from the base and at the same time seal the opening air tight.

To prevent the wire from being short circuited thru the rods connecting the two ends of the carriage, they were separated at the middle by hard fibre. This joint F was then covered with a tight fitting glass tube extending about half an inch beyond each end of the fibre insulations. This prevented the fibre from becoming coated with a layer of the conducting metallic deposit which would eventually accumulate on it and short circuit the wire.

The glowing silver wire, as mounted on the carriage, gradually evaporates and the vapor condenses on the material placed at P. This plane is about one inch below that of the wire. In order to cover a small area with an opaque deposit, it is only necessary to roll the carriage along its tracks so that the glowing wire is over the center of this area. A larger area can be covered when the wire is moved with uniform speed across it, so that the metallic vapor may condense uniformly. In order to move the heated wire it was necessary to have a mechanical control outside of the apparatus. This was supplied by means of a small crank which passed thru a ground glass stopper, sealed in the tube at R. This crank turned the horizontal, V-grooved wheel at A. Around this wheel passes a belt




Scale 2 cm = 1 inch.

to the small wheel Q, from where it passes to a hook on the carriage at F. The other end of the belt passes over a similar wheel at Q, and thence to a similar hook on the other side of the carriage.

By turning the crank R, the carriage can be rolled with any desired speed back and forth across the area between the tracks. This allows an area approximately equal to the area inclosed by the tracks to be covered with the metallic deposit.

In order to get a very pure deposit, it is necessary to use silver, free from other metals. The occluded gases, and absorbed impurities that naturally accumulate on the surface in the process of manufacturing and mounting the wire can be removed by heating it, when at one end of the tracks and away from the surface to be covered with the material. The gases thus driven off are removed by the pump and the impurities condense on the apparatus in the immediate vicinity of the carriage. The wire thus cleaned can now be rolled over the surface to be plated. To facilitate the deposition of opaque surfaces of silver especially where a slight admixture of platinum is not objectionable, it was found practicable to use an alloy of 15 per cent. platinum and 85 per cent. silver. Since the boiling point of silver is about 800°C. below that of platinum, it follows that silver can be rapidly removed by evaporation without melting the wire.

All the metals having a low melting point like zinc or tin, can be deposited very rapidly and with much ease from the well known alloys of brass and phosphor bronze. While those having a high melting point can be deposited from wires made out of the pure metal.

The advantage of this method over the chemical reduction process of depositing silver becomes apparent when one recalls the excessive care that must be exercised in cleaning the surfaces upon which the deposit is supposed to take place. In addition the often hopeless task of controlling the thickness of the deposit, when semi-transparent mirrors are required, is well known. The distillation method only requires the surfaces to be free from grease. This is easily accomplished by washing them in a bath of sodium hydroxide and then in some dilute acid. Rinsing off the acid and drying the surface with a clean lintless cloth completes the operation.

The surfaces upon which the deposition is to take place can be either plane, concave, convex or irregular. They can be any material, and even cardboard or paper can easily be covered with a mirror like surface if care

is taken not to deposit the material too rapidly or at too high a temperature. This method lends itself especially well to the making of galvanometer mirrors. In this apparatus the whole area between the tracks can be filled with the disks of glass and all simultaneously covered with a thick silver deposit, evaporated from the silver platinum alloy, in about one minute after the desired vacuum has been obtained.

The metal deposited by evaporation need not be polished, which is of great value when pure optical surfaces are wanted. Those made by other methods involving a chemical process always need some polishing with the inevitable adhesion of impurities.

Where semi-transparent silvered surfaces are desired, as those used in all interferometers, the procedure is as follows. A silver wedge is deposited by allowing the wire to stand over a microscope slide until the region just below the wire is opaque. In both directions at right angles to the wire the thickness diminishes with the distance. This wedge can then be examined for the required thickness which will produce the best combination of transmission and reflection. This region has a definite color by transmission which can be matched with the interferometer films undergoing deposition in the apparatus. To facilitate the color matching, place a white card under the interferometer plates. Since several plates can be silvered simultaneously it follows that all plates exposed to the vapor for the same length of time, have equal densities of metal deposited upon their surfaces.

In the chemical reduction of silver and its deposition on the plates no such exact results can be obtained. Here a thick film must be deposited and the surface gradually polished down to the required thickness. This usually requires great skill, and more often than not results in variations in thickness of the deposit and the adhesion of impurities. If the polishing is carried too far, the whole process must be repeated.

Similar deposits can also be produced by cathodic sputtering in vacuo. The objection to this method is not apparent at once. Its chief objection is, however, the slowness of deposition, and the penetration of the particles into the glass itself, which in turn results in a strain and a distortion of the reflected image, making the surfaces optically useless. The deposit also contains all the impurities found in the cathode.

The distillation method also allows one to resilver mirrors or surfaces

permanently attached to instruments without the necessity of removing them from their often delicately adjusted supports.

The instrument was built by Mr. Kalmbach, the laboratory mechanician, to whom I am indebted for some valuable mechanical suggestions.

Randal Morgan Laboratory of Physics
UNIVERSITY OF PENNSYLVANIA
Philadelphia
*March, 1917*

# A NEW TYPE OF COMPARISON PHOTOMETER

By P. G. NUTTING

The Martens comparison photometer* has for years been the favorite instrument for precision work in measuring relative transmission, reflection and relative brightness in general. It gives a good comparison field free from any perceptible dividing line. It gives the highest precision of which a visual instrument is capable and is so compact and well protected that it is seldom injured or thrown out of adjustment.

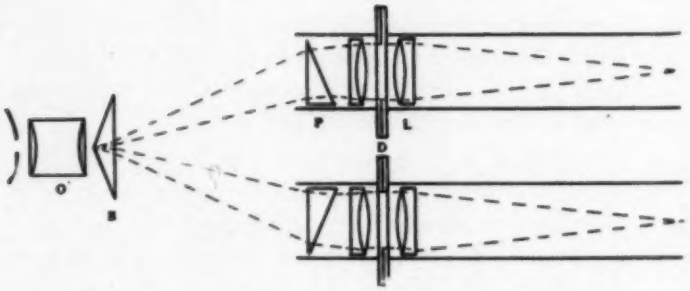
This is a polarization instrument, however, and if the light enters it in a partly polarized condition, either serious errors result or a tiresome duplication of readings is necessary to eliminate such errors. A much more serious objection, however, is that the instrument is no longer on the market, since the calcite for making the Wollaston and nicol prisms used for varying the light intensity in a known manner is not available. The new instrument was designed to do the precision work for which the Martens photometer is ordinarily used, but with more flexibility to take care of a wider variety of work. The use of calcite and of the polarization principle is avoided in its construction.

In the new type of instrument, the light beam is divided and recombined by means of bi-prisms and the density is controlled in a known manner by means of a precision iris diaphragm or neutral gray wedge inserted at the precise apex of the field pencils. The field viewed is bi-lateral and circular. The scale is empirical and very nearly linear. The two instruments constructed for the Research Laboratory of the Eastman Kodak Company have shown high sensibility and precision.

The construction of the instrument is as shown in the figure. The instrument is symmetrical about a longitudinal plane. In each beam a

*Phys. Zs. Vol. I, page 299, 1900.

lens, L, throws an image of the field on the apex of the bi-prism, B, of which the angles are equal to those of the wedges, P, used to deflect the beams. The field is viewed by means of the ocular, O, focused on the apex of the bi-prism. The lenses used are of short focus and symmetrical, light intensities are varied by means of iris diaphragms, D, which are very simply and carefully made. These diaphragms are carefully located at the intersection of object and image zone pencils. Hence, in viewing the image of the field at B, opening and closing the diaphragms varies the intensity of illumination over the whole field uniformly. It is upon this fundamental principle that the operation of the photometer depends, and practical tests of the completed instrument show that the condition is so well fulfilled that no departure from uniformity is perceptible to the eye.




For certain purposes the diaphragms are replaced by neutral tint absorbing wedges about six inches long and half an inch wide enclosed in glass plates, with a range of density from 0 to about 3.0. Such wedges may be obtained non-selective to within a very small error and with densities very nearly a linear function of the distance along the wedge. Wedge control is preferable for certain classes of work.

To increase the range of relative brightness measurable with this instrument, decimal gray filters about two centimeters square are inserted just in front of either of the two lenses in a brass box provided with suitable ways and light tight. The densities supplied are 0 (dummy), 1, 2, 3, 4 and 5. The corresponding transmissions are 1.0, 0.10, 0.0010, 0.00010, 0.000010 and 0.0000010. These filters are a commercial article and may be had with precision guaranteed to ½% of the whole transmission.

The dimensions of the instrument may be varied through wide limits by using lenses of different focal lengths and prisms of various angles.

The first model constructed was 16 inches long and the second 9 inches over all. The tubes on which the lenses were mounted are about two centimeters in diameter and lined with non-reflecting black felt paper.

As a *brightness comparator*, the instrument is used in its simplest form and is adapted to measure percentage transmission of thin objects such as photographic negatives. By stopping down the field apertures, the densities of small details may be readily measured. For such work, the illuminated field used as an accessory must be of extreme uniformity. Such a field we have found best obtained by placing a sheet of solid opal glass over the top of a white lined box containing an electric lamp. White drawing paper makes a good lining. The sheet of opal glass should be of pot opal rather than flashed opal, should be fine ground on both surfaces and of uniform thickness. If no lamp is available which does not give streaky illumination, a second plate of rough ground clear glass is placed an inch or two below the opal glass. This arrangement gives an exceedingly uniform illumination.

By means of various accessories attachable to the field ends of the photometer tubes, the instrument may be adapted for use as an illuminometer, brightness photometer, reflectometer, etc.

For use as a *brightness photometer*, a small light box is slipped over the end of the left hand tube, this box being white lined and containing a small, well seasoned lamp operated on storage battery. For determining the brightness of a distant object, a pair of lenses forming a simple Galilean telescope, such as half of a field glass, is placed axially in front of the right hand photometer tube so that an image of the distant object is thrown in the field plane of the photometer.

For use as an *illuminometer*, a white screen is mounted at a suitable angle about six inches in front of the right hand photometer tube, and an image of this thrown in the field plane of the instrument by means of a small auxiliary lens.

For use as a *reflectometer*, pairs of suitable reflecting or refracting prisms are placed over the field aperture of each photometer tube.

The chief advantage of this form of brightness comparator over the Martens is its freedom from errors due to polarization in the light to be measured. Like a Martens, its limit of sensibility is the limit of photometric sensibility of the human retina. Its scale is not quite as convenient as the circular scale, but the range of contrast to which the instrument is

applicable is very much greater. The instrument is simple in construction and comparatively inexpensive.

I am greatly indebted to various members of the staff of the physics division of the Research Laboratory of the Eastman Kodak Company for expert calibration of the scales and testing of sensibilities of these photometers.

Pittsburg
*June, 1917*

# A COMPENSATING FILTER IN SPECTROSCOPY[1]

By M. B. Hodgson and R. B. Wilsey

It would be desirable in many investigations in spectroscopy to have a photographic emulsion which would yield, in the same exposure, equal densities in the developed negative, over a wide spectral region, when using a light source having a continuous spectrum. While present day panchromatic dry plates show sensitiveness throughout the whole visible spectrum, and while the modern high efficiency illuminant is constant in radiant output and more uniform in spectral distribution than heretofore, such an ideal condition does not exist; the sensitiveness of the plate is not a constant value for all wave lengths nor is the energy distribution of the illuminant even approximately uniform.

To overcome these inherent defects, in obtaining quantitative or reliable qualitative analyses of absorption bands, various expedients are employed. One such consists in compensating for the lack of uniformity by using colored filters of selective absorption. With these (neglecting the further objection of the work involved in their preparation) it is difficult to get even approximate correction. A second method is to measure optically the density of the silver deposits in negatives exposed both through the medium whose transmission is being studied and without it. By proper computation and a knowledge of the sensitometric constants of the particular plate used, a measure may be had of the true absorption of the medium. This method, however, is open to many objections.

Recently Luckiesh[2] described a method which he has used with success in obtaining uniform photographic intensity throughout the spectrum, using a light source yielding a continuous spectrum.

[1] Communication No. 42 from the Research Laboratory of the Eastman Kodak Company.
[2] *Astrophysical Journal*, May 1916, p. 302.

The method, while not new in principle, having been first suggested by Morris-Airey[3] and tried to some extent by the authors a few years back, is an ingenious one and will give quick results when properly worked.

Briefly, the procedure is this:

The spectrum of the light source used is first photographed in the usual manner upon the particular brand of panchromatic plates selected, exposing through the glass, this last in order that re-focusing of the spectrum may be dispensed with in subsequent exposures. This initial negative is then developed, fixed, dried, and further exposures made, using it as a filter in contact with the emulsion of the print plate, its position coinciding with its original position, thus bringing the screen and print plate emulsion in approximately the same focal plane. The theory is that those portions of the spectrum which are most actinic will be restrained, in proper ratio, by the densities they have impressed upon the initial plate. Luckiesh gives several wave length transmission curves showing the efficiency of such filters and discusses their practical application.

Inasmuch, however, as Luckiesh does not enter into a discussion of the photographic side of the subject and since the authors have found the sensitometric constants to be all-important in determining the conditions for an approximately suitable filter and subsequent "print plate," it has been thought advisable to give the results of some experiments which they have made.

Theoretically the problem may be treated as follows:

Let $I_\lambda$ be the intensity of radiation of the wave length $\lambda$, $T_\lambda$ the transmission of the compensating filter at that point in the spectrum, and $S\lambda$ the speed or sensitiveness of the photographic emulsion for that particular wave length. Then

$$I_\lambda T_\lambda S_\lambda = K, \tag{1}$$

where K is a constant, is the condition necessary for obtaining equal densities for all wave lengths upon a photographic plate through the compensating filter.

In this method a silver deposit of transmission $T_\lambda$ is to be produced in the filter (a photographic negative) by the radiation $I_\lambda$. It will not be permissible for any subsequent treatment of the negative to alter this trans-

[3] T. Morris-Airey and S. H. Long, *Proc.* Uni. of Durham (Eng.) Phil. Soc., No. 5, page 119, 1912-1913.

mission selectively. Therefore, the negative must be developed in a developer giving neutral densities.

Density is defined in terms of transmission as follows:

$$\text{Opacity, } O_\lambda = \frac{1}{T_\lambda}$$

$$\text{Density, } D_\lambda = \log O_\lambda = -\log T_\lambda.$$

The condition (equation 1) to be fulfilled by the compensating filter may be expressed:

(2) $$D_\lambda = \log I_\lambda + \log S_\lambda - \log K.$$

$D_\lambda$ refers to the compensating filter and $S_\lambda$ to the emulsion on which further "prints" are to be made; the value of K is arbitrary, depending on the density produced in the print plate. It is only required that K be constant for all wave lengths.

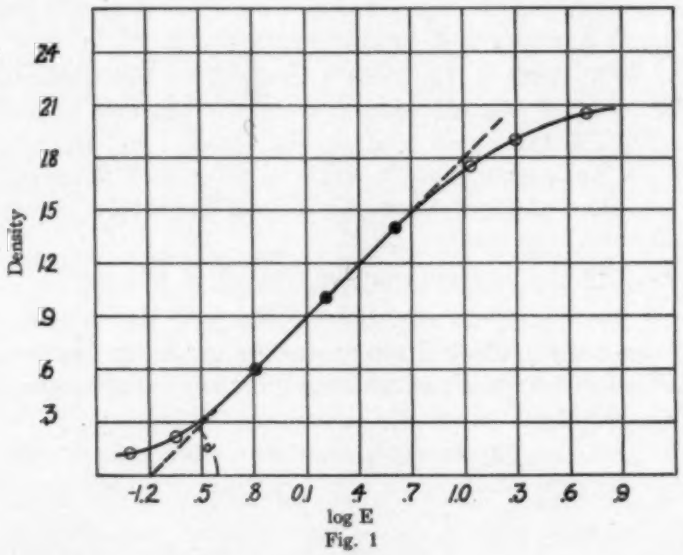


Fig. 1

In a photographic plate the relation

(3) $$D_\lambda = \gamma_\lambda (\log I_\lambda + \log S_\lambda)$$

holds over the range of exposures producing the straight line portion of the characteristic D – log E[4] curve. (See Fig. 1.) $D_\lambda$ is the density pro-

[4] Hurter and Driffield, *Journ.* Soc. Chem. Ind., May 1890. Sheppard and Mees, "The Photographic Process."

duced by the radiation of intensity $I_\lambda$. $\gamma = \tan \alpha$ (Fig. 1) and is determined primarily by the development of the plate and to some extent by the wave length of the incident radiation. $S_\lambda$ is the speed of the emulsion. Equation (3) will satisfy the requirements of equation (2) provided $\gamma_\lambda$ is unity for all wave lengths and $S_\lambda$ is the same in the two cases. This last condition is fulfilled by using plates of the same emulsion for making the compensating filter and subsequent print plates.

Since the toe and shoulder of the characteristic curve of the plate do not follow equation (2), those portions cannot be used in making a satisfactory filter.

The necessary conditions may then be summed up:

(1) The filter and print plate must be made on plates of the same emulsion.
(2) The filter must be neutral in color.
(3) All densities in the filter must lie on the straight line portion of the characteristic curve.
(4) The straight line portion of this characteristic curve must have a slope of 1 (*i. e.*, $\gamma_\lambda = 1$) for all wave lengths.

Such a compensating filter having been made; suppose it is desired to use the system to measure the spectral transmissions of a colored filter. A photograph made with this interposed in the path of the light will be of variable instead of constant density. If we know the form of the characteristic curve

$$D = (I_\lambda)$$

of the plate for each wave length and for a given development, then, upon measurement of the densities, the incident intensities may be calculated and the transmissions of the colored filter determined.

If $\gamma_\lambda = 1$ and the densities are all on the straight line portion of the curve, then

$$D_\lambda = \log I_\lambda + \log S_\lambda,$$

this equation now applying to the print plate made through the colored filter and compensating screen. Whence

$$T_\lambda \propto \frac{1}{T_\lambda}$$

and the reciprocals or the transmissions of the plate are proportional to the transmissions of the colored filter.

TABLE I

$\tan \alpha = 1.0$

Densities of filter on straight line portion of curve.

$D_0$ = Density of filter

$E_0$ = Exposure to give $D_0$

$E_1$ = Exposure through $D_0$

$D_1$ = Density resulting on print plate

| $D_0$ | %Tr | log $E_0$ | $E_0$ | $E_1$ | log $E_1$ | $D_1$ |
|---|---|---|---|---|---|---|
| 0.6 | 24.86 | −1.82+ | 0.668 | 0.166 | −1.146 | 0.15 |
| 1.0 | 10.0 | 0.22 | 1.66 | 0.166 | −1.146 | 0.15 |
| 1.4 | 3.99 | 0.62 | 4.17 | 0.166 | −1.146 | 0.15 |

TABLE II

$\tan \alpha = 1.0$

Densities of filter on toe and shoulder of curve.

| $D_0$ | %Tr | log $E_0$ | $E_0$ | $E_1$ | log $E_1$ | $D_1$ |
|---|---|---|---|---|---|---|
| 0.12 | 70.41 | −1.08 | 0.120 | 0.0845 | −2.92 | 0.10 |
| 0.22 | 60.60 | −1.35 | 0.224 | 0.135 | −1.13 | 0.14 |
| 1.75 | 1.77 | 1.04 | 10.96 | 0.194 | −1.29 | 0.20 |
| 1.90 | 1.25 | 1.30 | 19.95 | 0.245 | −1.39 | 0.25 |
| 2.05 | 0.89 | 1.70 | 50.12 | 0.450 | −1.56 | 0.45 |

TABLE III

$\tan$ = 1.5

| $D_0$ | %Tr | log $E_0$ | $E_0$ | $E_1$* | log $E_1$ | $D_1$ |
|---|---|---|---|---|---|---|
| 0.25 | 56.79 | −1.46 | 0.288 | 1.63 | 0.21 | 1.10 |
| .035 | 45.16 | −1.65 | 0.447 | 2.02 | 0.30 | 1.24 |
| 0.6 | 24.86 | −1.88 | 0.759 | 1.89 | 0.28 | 1.21 |
| 1.0 | 10.0 | 0.15 | 1.41 | 1.41 | 0.15 | 1 0 |
| 1.8 | 1.59 | 0.68 | 4.79 | 0.76 | −1.88 | 0.60 |
| 2.25 | 0.56 | 1.01 | 10.23 | 0.57 | −1.76 | 0.45 |
| 2.4 | 0.39 | 1.20 | 15.85 | 0.62 | −1.79 | 0.46 |

* $E_1 \times 10$ in each case.

To illustrate:

Figure 1 shows the characteristic curve of a Wratten Process Panchromatic plate exposed to white light when developed to such an extent that the slope of the straight line portion is unity (tan $\alpha = 1$). The solid circles along the straight line portion represent the various densities of a satisfactory "template." In Table I are given the "sensitometric constants" for these densities, *i.e.*, the transmission (visual) of the screen plate and the resultant densities of the print plate, when the two are developed under the same circumstances which give the condition tan $\alpha = 1$, for exposure to white light. This last assumption, that the contrast of a photographic plate with wave length is constant and the same as for white light, is only approximately correct and varies greatly with different emulsions. In the particular plate used in this investigation the factor does not seem to be of great moment.

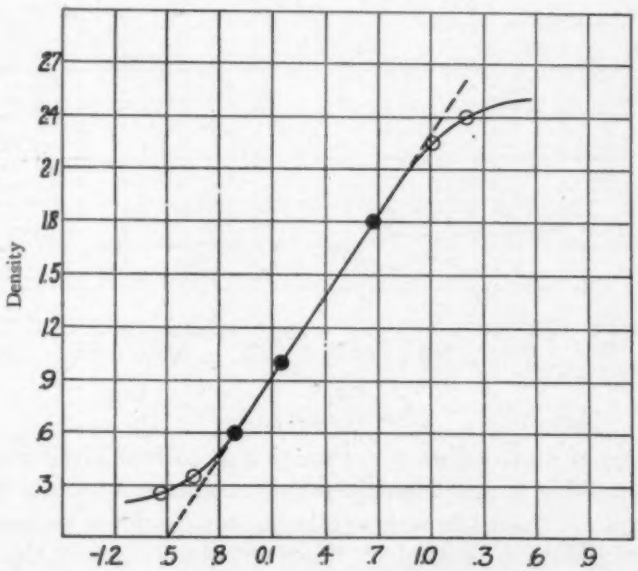


Fig. 2

From Table II it will be seen that the resultant densities on the print plate are quite uniform, enabling further exposures through some selective absorbent to be easily interpreted correctly. In Table II the constants

are given in the case of densities which do not fall upon the straight line portion. These densities are indicated in Fig. 1 by clear circles. These densities on the shoulder or over-exposure portion of the curve under correct, while those upon the toe or under-exposure portion over correct, which, of course, follows from the non-conformity to the straight line proportionality. In Fig. 2 is shown the resultant characteristic curve of the same brand of plates (exposed to white light) when developed to a contrast of 1.5 ($\tan \alpha = 1.5$). The departure of the densities of a print through a template similarly developed (*i.e.*, time of development of template equals time of development of white light exposures to $\tan \alpha = 1.5$) from a constant value is seen in Table III.

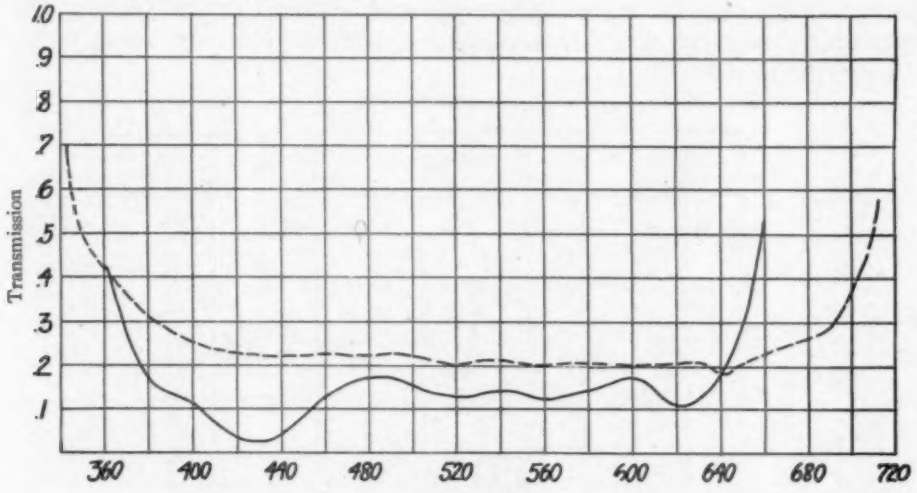



Fig. 3

In practice the procedure for obtaining a correct filter would be as follows: By making a graduated series of exposures to white light after the Hurter and Driffield method, varying in some known progression and developing for different lengths of time, we obtain, when the resultant densities are measured and plotted as a function of the exposure (usually $D - \log_{10} E$), the characteristic curve of that particular plate, the slope of the straight line portion varying with developing time. Given the proper development we obtain a curve such as shown in Fig. 1, with the straight line portion satisfying the condition $\tan \alpha = 1$.

We may then note the limiting densities on the straight line portion. This gives us a criterion for selecting the proper filter. A series of exposures may then be made on the spectrograph after the manner employed by Luckiesh and developed for the same length of time, which we found gave the condition tan $\alpha = 1$, in the case of white light. Those templates whose extreme densities lie upon the straight line portion are then ready for use as filters.

The writers have found that by using this method they are able to obtain satisfactory spectrograms for qualitative or quantitative analysis of absorption spectra. An illustration of typical cases is given in Figs. 3 and 4. The plate used is Wratten Process Panchromatic. In Fig. 3 the solid line represents the original wave length-transmission curve of a filter made according to the foregoing specifications.

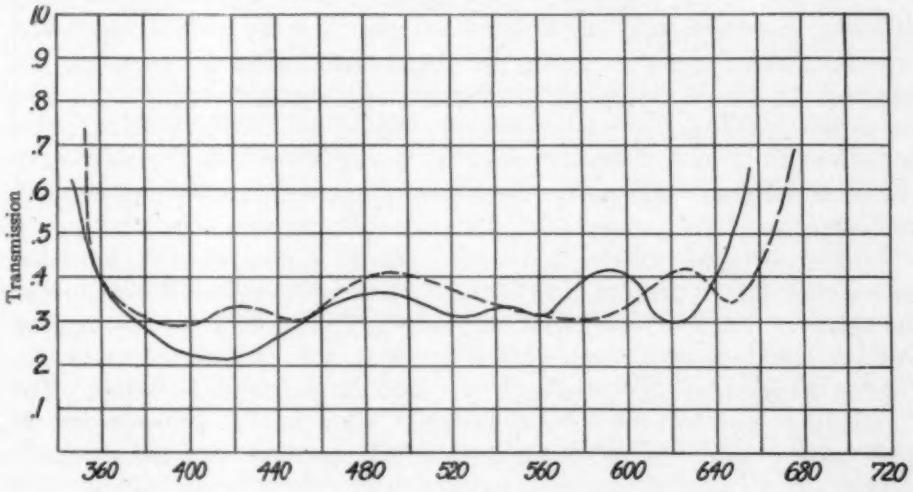



Fig. 4
Wavelength in μμ

The dashed line represents a print through this same filter. In Fig. 4 corresponding lines indicate a filter and the resultant print through, *not* conforming to specifications.

It is, of course, obvious in all cases that the extreme ends of the spectral region of plate sensitiveness may never be fully corrected owing to densities of the template in these portions rapidly falling below the straight line portion.

To secure a silver deposit of neutral absorption the authors have used elon developer. Ferrous oxalate developer is even better in securing approximately non-selective densities.

Research Laboratory
EASTMAN KODAK COMPANY
Rochester, N. Y.
*December 11, 1916*

# STELLAR IMAGES ON A PHOTOGRAPHIC PLATE AS AFFECTED BY DEVELOPMENT

PRELIMINARY PAPER[1]

By F. E. Ross.

The size of the image of a star impressed upon a photographic plate depends upon telescope, upon the star color and magnitude; upon the exposure time, character of plate, developer and time of development. It occurred to the writer since developers vary in their action upon the latent image that possibly an extremely faint stellar image undevelopable or at best ill-defined, through the action of one reducer, might be brought out more strongly and made measurable through the reducing action of another.

An artificial star cluster was used composed of nine holes of graduated sizes arranged in a circle on a lantern slide plate with a close double star at the center. This was placed at the end of a rigid tube 20 feet long, at the other end of which was placed an especially well corrected photographic objective of aperture ratio 5.3 and focal length 6 inches. The illumination was furnished by a tungsten lamp and a diffusion screen. Such an exposure was given as to make the smallest artificial star just visible or on the threshold of vision when developed. Among the developers tried were: Pyro, Caustic-Hydrochinon and Metol-Hydrochinon (MQ)-25; the development time was varied in each case. The conclusion was that there is very little difference in developing a threshold star or a just discernible but unmeasurable image. The writer is tentatively of the opinion that Pyro developing for a comparatively short time to a contrast of about unity gave the best results of any in this respect. This needs to be checked, however.

[1] Communication No. 47 from the Research Laboratory of the Eastman Kodak Co. Presented before the Optical Society of America at the New York meeting held December 28, 1916.

Of more immediate importance is the question as to the developing power on star images one step removed from threshold or images which are really measurable. As to this question there is no doubt in the writer's mind but that Caustic-Hydrochinon proved in the test to be the superior of any developer tried. There is a jet blackness about star images developed with this reducing agent which holds down to the faintest measurable stars. With other developers the faint images become gray and diffuse, without the solid black centers formed with the Caustic-Hydrochinon. The development, as with all developers, should be pushed to the limit to make measurable the faintest stars. This point will be returned to again.

A matter of probably greater importance is connected with the accuracy of measurement of star images. Is there a choice of developers and development time where extreme accuracy in the measurement of the distance apart of stellar images is sought?

When the images to be measured are far apart, several factors enter into the accuracy with which their distance can be determined. One of the most important is the distortion of the film. When the original emulsion has been evenly dried on the plate by the maker, and when the user of the plate likewise dries it evenly after development and washing, distortion errors are inappreciable. The most serious error remaining is that due to the frequent uneven borders of a star image, making its bisection a matter of some misgivings. Little is known as to the cause of this phenomenon. Possible explanations are: Non-symmetry in the light such as is produced by coma in a telescope; purely chance distribution of the silver grain; lack of uniform setting of the emulsion, so that small regions abound where there is a scarcity of silver bromide grain; lastly, action of the developer, which is the effect now to be considered.

An instrument has recently been designed by Dr. P. G. Nutting and the writer to accurately measure the sharpness of images on a photographic plate. In order to overcome the lack of definition of a lens system, contact prints of an accurate knife edge were made on photographic plates. The action of developers was studied on these prints, the density gradient being measured in each case. It was found that the Caustic-Hydrochinon developer gave the sharpest edge of all those tried. The presumption is therefore strong that the ragged edge effect in a star image would be less marked when this developer was used, and, if less ragged, greater accuracy in measurement should be obtained. To actually test the matter, 20 images of the cluster were photographed on 4 plates, in the long camera

described above. The plates were developed in Caustic-Hydrochinon and Pyro for 2 and 8 minutes. The distance between adjacent stars was then measured for all the clusters on a comparator, means taken, and the probable error of a single measure of distance deduced. The results are shown in the following table, where the mean value from 4 separate star pairs is given. Each probable error, therefore, depends upon 80 measures.

PROBABLE ERROR OF A SINGLE MEASURED DISTANCE.

| Only one bisection of each single star was made. Distance between stars = ¼ mm. | p. e. | Average distance |
|---|---|---|
| Plate developed in Pyro for 2 minutes..... | 1.56$\mu$ | 241.1$\mu$ |
| Plate developed in Pyro for 8 minutes..... | 1.46 | 241.5 |
| Plate developed in Caustic-Hydrochinon 2 minutes | 1.09 | 240.8 |
| Plate developed in Caustic-Hydrochinon 8 minutes | 1.33 | 240.7 |

Considering the average distance obtained first, there appears to be a systematic difference in the measured distance depending upon the developer, but not the time of development. This result, however, needs to be checked by a longer series of observations. Under conditions actually existing in astronomical work, the systematic development error should be larger than here indicated, since these experiments were performed under exceptionally favorable circumstances. Concerning the accuracy of measurement under different development conditions, there does not appear to be a doubt. Unquestionably the images developed for 2 minutes in Caustic Hydrochinon have been measured with the greater accuracy. Since the probable errors given include the accidental errors of observation the relative development errors will be much larger than the ratio of the above numbers indicate. This result is supported by two other independent lines of evidence. First the sharpness of knife-edge prints developed in Caustic-Hydrochinon exceeded that obtained with any other developer. Second, the cleanness of the stellar image on these plates is such that greater accuracy in their measurement is at once apparent.

An important corollary, deducible from the smallness of the probable error of a single distance, is that there is no sensible distortion of the film. What might be confused with such local distortion are: edge effects due to developer, non-uniform distribution of grain, and instrumental aberrations.

Evidently the question as to how far the development of stellar plates should be carried is an important one, when the accuracy of their measurement is the main consideration. If development is pushed to the limit, the outermost border of the image, where there is very little gradation of light, is developed, with the result that fuzzy edges are obtained. But if only the central portion of the latent image is developed, as happens when a short development time is chosen, the edges are sharp and contrasty, because in that case development stops on the steep portion of the light curve.

The rate of growth of the image with increasing intensity or exposure time is a simple phenomenon. The rate of growth with development time appears to be more complex. One might expect, for example, that all developers would give the same size of image if the development times were chosen so as to give equal contrast or gamma[2] in the Hurter and Driffield system. But such does not appear to be the case. With Pyro and M.Q. 25 as a developer, doubling gamma does not affect the size of the image to any proportionate extent, while with Caustic-Hydrochinon and others the size increases steadily and rapidly with the development time. The exact relationships are being obtained. The effect of wave length is also to be considered. It has already been shown by the writer that a knife-edge print on a plate exposed to blue light gives a much sharper edge than when the same edge is exposed to green or red light. The maximum sharpness has been found for all emulsions at wave length 400$\mu$, the minimum at 500$\mu$, the difference amounting to 300 per cent.

Through the double star forming part of the cluster, data have been obtained on the resolving power of plates as affected by development. It is commonly supposed that close double stars cannot be resolved on the photographic plate, and the emulsion has been blamed for this ineffectiveness in double-star investigation. But the result obtained by the writer shows that the blame must be placed elsewhere, probably upon the telescope and the atmosphere. For with Seed 23 plates, resolution of the two components of the double star was sharp and unmistakable, although separated by only 0.027 mm. Now in a telescope of 18 meters focal length this corresponds to an angular separation of 0.″30. If the finer grained lantern slide plate is used, the resolving power is twice this amount.[3] In

[2] Gamma is by definition the tangent of the slope of the straight line portion of the curve made by plotting density against logarithm of exposure.

[3] Since this was written the writer has obtained resolution of double stars, the distance between whose centers was but 11$\mu$. Seed lantern plates were used.

other words, double stars of only 0."15 separation could be resolved and measured provided this does not exceed the visual resolving power of the telescope. The two components should be nearly equal in size, which would, of course, limit the application of the photographic method.

*Formula for Caustic-Hydrochinon:*

| SOLUTION A | | SOLUTION B | |
|---|---|---|---|
| Hydrochinon | 1 oz. | Caustic Potash | 2 oz. |
| Meta-bisulphite of Potash | 1 oz. | Water | 40 oz. |
| Bromide of Potash | 1 oz. | | |
| Water | 40 oz. | | |

Use equal parts and develop at 65° ± 2°. Rinse one minute before fixing. Caustic Soda may be used in place of Potash.

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# ABSTRACTS

A PROPOSED METHOD FOR THE PHOTOMETRY OF LIGHTS OF DIFFERENT COLORS. I. G. Priest, Phys. Rev. 9, p. 341, April 1917. The color difference is eliminated by means of the rotatory dispersion of quartz. Light from the comparison source is polarized by nicol no. 1; a quartz plate rotates the plane of polarization differently for various wave-lengths; the color of the comparison field is then varied by a second nicol behind the quartz plate, and its intensity is varied by a third nicol. Its intensity is computed from the visibility of radiation curve, the spectral energy curve of the source, the spectral rotation of the plane of polarization by the quartz, and the angles of rotation of the nicols. A test showed the method to agree very well with an equality of brightness determination with color difference present.

STUDIES OF THE ULTRAVIOLET TRANSPARENCY OF CERTAIN COLORED MEDIA. H. W. L. Absalom, Phil. Mag. 33, p. 450, May 1917. By means of a quartz spectrograph, the wave-lengths in the ultraviolet at which absorption begins was determined for a number of gems, minerals, and solutions of metals in liquid ammonia. One general result is that transparency far into the ultraviolet is much more commonly met with in the case of color due to cooloidal metals than has been found to be in ordinary colored salts or aniline dyes.

THE ROTATION OF PRISMS OF CONSTANT DEVIATION. W. E. Forsythe, Astrophys, J. 45, p. 278, May 1917. It is shown that if a constant deviation prism be rotated about the line of intersection of the bisector of the ninety degree angle of the prism and the reflecting face, the prism will remain in the position of minimum deviation for all wave-lengths; i. e., there will be no lateral shift of the beam. By the aid of diaphragms, the prism may also be adjusted so that the telescope objective is illuminated symmetrically.

THE PHYSICAL BASIS OF COLOR TECHNOLOGY. M. Luckiesh, J. Frank, Inst. 184, p. 73, July 1917. The author reviews the various methods of analyzing color, of which the most important is the spectro-photometric. The three classes of colored media, namely pigments, dyes and vitrifiable colors are discussed and the bases of their colors and the factors influencing them are given.

The spectral analyses of a number of pigments are presented, together with their luminosity curves and reflection factors for the common illuminants.

A POLARIZATION FLICKER PHOTOMETER AND SOME DATA OF THEORETICAL BEARING OBTAINED WITH IT. H. E. Ives, Phil. Mag. 33, p. 360, April 1917. The polarization flicker photometer is a combination of a double image prism with a rotating nicol prism. The double image prism superposes the horizontally polarized image of one half the photometric field upon the vertically polarized image of the other half. The nicol prism as it rotates alternately extinguishes each image, the one fading gradually into the other, with entire absence of any mechanical edge effect. The brightness of the image of each half of the photometric field varies as the square of the cosine of the angle of rotation of the nicol.

This photometer has been used to verify the

theory of the flicker photometer as developed previously by the author and E. F. Kingsbury.

THE APPLICATION OF THE PLANE GRATING TO THE DETERMINATION OF THE INDEX OF REFRACTION OF A GAS. R. W. Dickey, Astrophys. J. 45, p. 189, April 1917. The Littrow form of spectrometer was used. The grating was covered by a bell jar, which was connected to a vacuum pump. The shift of the spectrum lines was observed when the contents of the bell jar was changed from a vacuum to a gas, and the indices of refraction were computed from this shift. The only serious difficulty was found to be one due to changes of temperature. The dispersion curve of air was determined from $\lambda=6412$ to $\lambda=2493$. The accuracy of the values of the index of refraction agrees with those of other methods.

"ON THE REFRACTOMETRY AND IDENTIFICATION OF GLASS SPECIMENS, ESPECIALLY LENSES." Mr. L. C. Martin, A. R. C. Sc., B. Sc. (*"The Optician and Scientific Instrument Maker," December 29, 1916, and January 5, 1917.*) The article consists of the description of a method for measuring the refractive index of glass specimens of any form excepting those approximating a plane parallel plate, by submersion in a liquid of variable refractive index, and the description of "two direct reading instruments for measuring curvature."

The writer claims that the method of submersion as described by him is capable of giving the refractive index to 1 in the 4th decimal place and that it will allow of the determination of dispersion; also that these determinations may be made with the usual sources of light, i. e., a sodium flame and a hydrogen tube. The novelty of the method lies in the facts that mechanical stirring of the liquid is resorted to, to keep it homogeneous, and that two mixtures of liquids are recommended that give a gradual and continual change of refractive index. They are, carbon disulphide with alcohol giving a range from 1.3617 to 1.6277, and carbon disulphide with benzol, giving a range from 1.5003 to 1.6277.

The two "direct reading instruments for measuring curvature" are good only for convex surfaces. The first apparatus measures the curvature in terms of the distance from the axis of the lens to which a ray of light will be reflected when allowed to fall on the lens parallel to the axis and at a fixed distance from it. The second apparatus consists of a pendulum rod upon the end of which is fastened the lens. The point of oscillation is moved along the rod until it coincides with the center of curvature of the surface of the lens, which condition is determined by the immovability of the image of a distant object formed by reflection in the surface of the lens. The writer claims that with proper means for observing the image and measuring the distance from the surface of the lens to the point of oscillation, the radius of curvature may be determined to 0.5 per cent. by several determinations.

COLOR TEMPERATURES OF ILLUMINANTS. E. P. Hyde and W. E. Forsythe, J. Frank. Inst. 183, pp. 353–4, March, 1917. The temperature of a black body which will match a given illuminant in color is called by Dr. Hyde the "color temperature" of that illuminant. This datum is more easily visualized than the spectrophotometer curve or the measurements obtained with either type of colorimeter. The method is easily applicable to nearly all illuminants, the exceptions being such sources as the Welsbach mantle, the mercury arc and other sources which can not be matched in color with a black body at any temperature.

Data for some of the most common illuminants are given in the table.

COLOR TEMPERATURE OF VARIOUS ILLUMINANTS

| Source | Color Temp. °K |
|---|---|
| *Gas flame, fish tail burner | 1870 |
| Hefner | 1875 |
| Pentane (10 candle-power standard) | 1914 |
| Candle: | |
| Paraffin | 1920 |
| Sperm | 1925 |
| Kerosene lamp: | |
| Round wick | 1915 |
| Flat wick | 2045 |
| Acetylene (as a whole) | 2368 |
| One spot | 2448 |
| 2.3 w. p. h. c. Nernst glower | 2388 |
| 4.0 w. p. h. c. carbon | 2070 |
| 3.1 w. p. h. c. treated carbon | 2153 |
| 2.5 w. p. h. c. Gem | 2183 |
| 2.0 w. p. h. c. Osmium | 2176 |
| 2.0 w. p. h. c. Tantalum | 2249 |
| 1.25 w. p. h. c. Tungsten | 2385 |
| 0.9 w. p. h. c. Tungsten | 2543 |
| 0.5 w. p. h. c. Gas-filled Tungsten | **2900 |

*Coal and water gas mixture. Approximately 600 B.T.U.

**Approximate. Differs with different lamps.

NEW APPARATUS SHOWN AT THE OPTICAL SOCIETIES EXHIBITION. Engineering 103, pp. 60–61, Jan. 19, 1917. At the third quinquiennial exhibition of the Optical Society of Great Britain, a number of interesting pieces of apparatus were exhibited.

Two instruments for measuring the angle between the axes of binoculars were exhibited; one by R. S. Clay and another by C. B. Drysdale. Clay's apparatus consists of a lamp, collimator with scale, lateral slide to carry binoculars under test and an observing telescope with ocular scale. Without the binocular inserted the collimator and telescope scales coincide. When either component of the binocular is interposed the scales appear superposed, but of different length, the relative lengths indicating the magnification. If the optic axes of the two components are parallel, the appearance should remain the same whichever of the two is slid into position.

Drysdale's apparatus exhibited by Messrs. Tinsley and Co. consists of two collimators fixed vertical side by side, each having an Osram lamp fitted into its lower end. The two collimator beams are brought to a common focus by a large thin lens of

one meter focal length. A bright disc is then seen on a horizontal screen above. When the binocular pair is placed immediately above the collimator pair the bright disc will appear simply enlarged if the axes are parallel. If not parallel, the bright disc will appear divided into four sectors, more or less displaced. The amount of the displacement, measured on a ruled screen, gives the amount of deviation from parallelism. If the reflecting prisms of the binocular are twisted, the quadrants of the bright disc appear rotated instead of simply displaced.

A weathering test for glass was exhibited by H. Jackson, of King's College. The prism or other piece of optical glass to be tested is subjected to the action of steam in an autoclave for several hours. Glass which would show considerable weathering in ordinary use, subjected to this treatment, appears like a piece of ice with snow crystals adhering or shows other features characteristic of the glass.

A test for parallax in telescopic rifle sights was exhibited by the Optical Department of the Ministry of Munitions. An artificial eye moved by a slide is used much as the eye of an observer is used in a rough test, but moving in machined ways is capable of higher precision. The observing telescope is provided with a vertical pointer and two cross lines. In the absence of parallax the pointer keeps its position with respect to the cross lines when the pupil is shifted.

SIMPLE RANGE FINDER AND CLINOMETER. C. R. Young, Eng. News, 76, pp. 1183–1184, Dec. 21, 1916. A simple instrument for roughly determining distances, which has been used successfully for military reconnaissance surveys and field sketching. It is based on the fact that the heights of familiar objects in the landscape, e. g., houses, telephone poles, doors, animals, men, can frequently be judged from experience, and from these the ranges or distances are easily determined. A rectangular piece of opaque white celluloid, 3 x 6 in., is furnished with a scale on one edge, and has a cord attached whose length, 25 in., is equal to 1000 divisions of this scale. The card is held vertically at arms length, the cord kept taut with the free end next the eye, and the number of scale divisions ($y$) required to cover the object sighted is read off. If $H$ be the true height, $y$ the apparent height of the object, $x$ the range and $c$ the length of the cord, obviously $xy = cH$, which is the equation of a rectangular hyperbola referred to the asymptotes. The body of the card is covered by a cross-ruled diagram with a series of fifty hyperbola arcs, corresponding to fifty values of the estimated height $H$, and having as common asymptotes two edges of the diagram. Selecting the proper hyperbola, the range $x$ corresponding to any observed apparent height $y$ can be read off on a scale along an asymptote. The scale of $y$ on the diagram is four times greater than on the edge scale used for observation. The device may also be used to measure the height of an object whose distance is known. The reverse side of the card has a table of dimensions of common objects, and also a scale of angular divisions, so that by attaching a plumb-bob to the cord, the instrument can be used as a clinometer.

PHOTOMETRY OF RADIO-ACTIVE LUMINOUS COMPOUNDS. N. E. Dorsey, J. Wash. Acad. Sci., 7, pp. 1-6, Jan. 4, 1914. Contribution from the Bureau of Standards. A special photometer was devised and is in use at the Bureau of Standards for the measurement of the surface brightness of various self luminous radio-active compounds. The photometer box is provided with a window of opal glass illuminated from behind with a movable lamp of constant intensity. The sample of material whose brightness is to be determined is placed in a cylindrical glass tube which is blackened over two-thirds of its circumference. The brightness of the unblackened portion is compared with that of the opal glass window of variable brightness. The precautions which are necessary to obtain the highest sensibility and precision are described. Brightnesses of such substances as zinc sulphide, willemite, and barium platinocyanide are of the order of 10 microlamberts, i. e., 0.01 equivalent candle-feet.

SOME CRITICAL FREQUENCY DATA OBTAINED WITH A NEW FORM OF FLICKER PHOTOMETER. Herbert E. Ives, Phil. Mag. 33, pp. 360–380, April, 1917. In most ordinary flicker photometers the transition between alternate fields is abrupt. Dr. Ives has designed a new form in which the transition is a sine function of the time. Two adjacent photometric fields are viewed through a nicol prism and a double image prism. As the nicol prism revolves at constant rate, it alternately extinguishes the image of each field, the one merging gradually into the other with entire absence of any mechanical edge effect.

This new photometer is used to check theoretical conclusions arrived at in an earlier publication as to the critical frequency relation in alternate fields of various relative brightnesses in various relative colors. The data obtained with the new form of flicker photometer agree closely with those predicted by Dr. Ives' diffusion theory of retinal action.

# FALL MEETING, AMERICAN PHYSICAL SOCIETY

At the invitation of the Bausch & Lomb Optical Co., Eastman Kodak Co. and the Taylor Instrument Companies, the fall meeting of the American Physical Society will be held in Rochester, N. Y., on Friday and Saturday, October 26th and 27th. The opening session will take place at the Hotel Seneca on Friday morning, while the meetings on Friday afternoon, Saturday morning and Saturday afternoon will be held at the Bausch & Lomb Optical Company's Works, Taylor Instrument Companies' Factory. and Kodak Park respectively. In addition to the papers read by the members of the Society, a number of papers will be given by members of the Scientific Staffs of the different establishments.

A dinner followed by a smoker will be given on Friday evening.